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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
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NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal,* should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 19, NO. 1, PP. 3–25
FIGS. 1–4, APRIL, 1949

RESULTS AND PROBLEMS OF HEAVY MINERAL ANALYSIS IN GERMANY: A REVIEW OF SEDIMENTARY-PETROLOGICAL PAPERS, 1936-1948

F. K. HEINZ SINDOWSKI
Hanover, Germany
Edited by Prof. Lincoln Dryden, Bryn Mawr College, Bryn Mawr, Pennsylvania*

ABSTRACT

The progress of research in sedimentary petrology in Germany during the years 1936–1948 is reviewed and discussed; particular attention is paid to heavy-mineral analysis. In order to make a survey of the numerous papers a uniform one, units and terms employed have been modified where necessary; for example, all mineral frequencies have been expressed as percentages. Except in the discussion of methods and problems, the treatment is by stratigraphic units.

1. INTRODUCTION

Though Thürach, in 1880, had already begun work with heavy minerals, forty years passed before this method came to be generally adopted in Germany. In the early days of its general adoption, the method was applied only to zoning sedimentary rocks devoid of fossils. Later on, paleogeographical problems came to play a larger and larger part; for example: provenance of the minerals; effects of sorting and grading during transportation; and, the selective effects of weathering before and after their incorporation in sedimentary rocks.

During the period 1936–1948, the following universities and research workers have played a major part in German heavy-mineral studies:

Hamburg (H. Deecke, H. Kleinsorge, Müller, W. Richter, Simon)
Heidelberg (W. Richter, K. H. Sindowski, R. Weyl)
Kiel (H. Steinert, W. Wetzel, R. Weyl)
Cologne (G. Eberich, W. Kahmann, J. Rohling, K. H. Sindowski)
Munich (H. Andrée, G. Claus, F. Neumaier, H. K. Zöbelein)
Rostock (W. v. Engelhardt, V. Leinz)

2. METHODS

In Germany, the sedimentary rock is usually divided into its various size fractions (grades) before the heavy minerals are separated. Most commonly, the following six grades are employed:

1. 0.5–0.4 mm. medium sand C
2. 0.4–0.3 mm. medium sand B
3. 0.3–0.2 mm. medium sand A
4. 0.2–0.1 mm. fine sand
5. 0.1–0.05 mm. very fine sand
6. 0.05–0.01 mm. silt

The fractions of grain sizes 0.5 to 0.1 mm. are separated by sieving, those below 0.1 mm. by elutriation. Many workers avoid elutriation because the results obtained may not be comparable with those of sieving.

The fraction to be used for heavy-

* This paper, written in English, has been given minor revision and rephrasing. Many of these changes could not be submitted to the author, so that any inaccuracies or inconsistencies are to be attributed to the undersigned. In the bibliography, those references which are included in the Geological Society of America "Bibliography and Index of Geology Exclusive of North America," through 1947, have been revised in the format given therein, and pagination has been added; references not included have been given in the form submitted by the author.

Text figures have been redrawn by Miss Elenore Schewe of Bryn Mawr College. On the map, and in the text, there may be minor inconsistencies of spelling—such as "Schleswig-Holstein" and "Schleswick-Holstein"—but it is believed that such variants will not be confusing.—Lincoln Dryden.

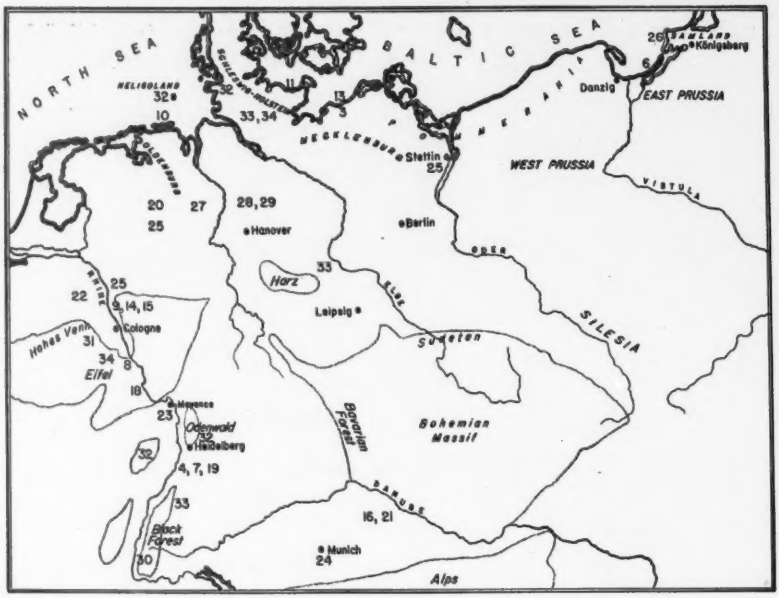

FIG. 1.—Map of Germany, showing localities of heavy-mineral studies. Numbers on the map refer to numbers of Tables in the text.

mineral separation is usually boiled for a short time in HCl. Separation is carried out in a heavy liquid of specific gravity 2.8–2.9, in a separatory funnel or centrifuge. A high-speed centrifuge is employed if the quantity of heavy minerals is to be ascertained.

After mounting in a suitable medium, like Canada balsam, the grains are counted under the microscope. In some cases, all the grains are counted; in others, count is made along several traverses across the field. It is the general custom to number separately the transparent grains, and the cloudy and opaque grains together with mica. Frequently, only the percentages of transparent grains are given, in which case the sum of these percentages is taken as 100%.

There is a great difference of opinion as to the number of grains that must be counted to give truly representative frequencies. The usage of various workers is shown in Table 1.

TABLE 1

Author	No. of grains counted
Kahmann 1936	100
Erberich 1937	150–200
W. Richter 1937	250
Friedler 1937	200–400
Claus 1936	200–300
Zöbelein 1939	300
Sindowski 1938	300–400
Andrée 1936	300–500
W. Richter 1939	400–500

More recently, Sindowski has shown that a count of 200 transparent grains is sufficient, particularly if there are a considerable number of separations from the same bed.

Some writers, however, only list the minerals in order of their frequency (W.

Wetzel), or assign arbitrary numbers indicating relative frequency (Sindowski, Weyl).

3. SELECTION OF GRAIN SIZES FOR HEAVY-MINERAL ANALYSIS

The choice of grain size, or sizes, for heavy-mineral separation is of great importance, as is the question of whether the choice should be the same for different sediments.

Original size, and sorting are the two chief factors which determine the proportions of various minerals in each grain size. If igneous rocks are the source of the heavy minerals, garnet, augite, kyanite, and tourmaline are most common in medium sand, while zircon and rutile are most abundant in fine and very-fine sand. Claus, and Kleinsorge have shown that zircon is always smaller than 0.2 mm. But if the source is sedimentary rocks, the heavy minerals will generally be smaller, because of weathering and reworking.

The choice of grain size must be based above all on the mechanical composition of the sediment in question. In general, the modal size (the size having highest frequency) and the two successively finer sizes have greatest significance.

Before 1938, nearly all German sedimentary petrologists used only the one grain size which they considered most suitable. The following survey, Table 2, shows the selections made by various workers.

A few examples will show how heavy-mineral frequencies vary as a function of grain size.

TABLE 2

Selection of grain sizes	
1. Not sieved and not elutriated:	
Engelhardt 1938	for medium sands
Zöbelein 1939	for clays and marls
Neumaier 1940	for clays and marls
2. Grain size 0.4–0.2 mm. diameter:	
Kahmann 1936	for coarse sands
Erberich 1937	for coarse sands
3. Grain size 0.25–0.1 mm. or 0.2–0.1 mm. diameter:	
Claus 1936	for detritus of igneous rocks
Dechend 1937	for medium sands
Rohling 1940	for fine sands and silt
Sindowski 1937–38	for medium and fine sands, tuffs
Weyl 1938–48	for fine sands, marls, clays
Steinert 1948	for boulder-clays
4. Grain size 0.2–0.05 mm. or 0.2–0.02 mm. diameter:	
H. Andrée 1936	for fine sands, marls, clays
H. Deecke 1935	for fine sands, marls, clays
W. Richter 1947	for fine sands, marls, clays
5. Grain size 0.1–0.05 mm. diameter:	
Fiedler 1936	for boulder-clays
W. Richter 1938	for boulder-clays
Scheidhauer 1939	for very fine sandstones
6. Other grain sizes:	
W. Richter 1939—0.5–0.2 mm. and 0.2–0.05 mm. for sands	
Kleinsorge 1937—0.5–0.2 mm. and 0.2–0.02 mm. for sands	
Sindowski 1938–48—0.3–0.2 mm. and 0.2–0.1 mm. and 0.1–0.05 mm. for sands	

TABLE 3. *Mecklenburghian beach sand of the Baltic Sea*
(after Sindowski 1938)

Heavy minerals	0.4–0.3 mm.	0.3–0.2 mm.	0.2–0.1 mm.
tourmaline	9	11	4
zircon	1	—	2
rutile	5	6	3
garnet	42	7	30
kyanite	6	8	4
staurolite	2	4	3
andalusite	1	2	1
epidote	2	8	2
amphiboles	1	22	8
augite	—	3	2
titanite	—	1	1
olivine	—	3	1
opaque	19	13	35

A Mecklenburghian beach sand (Table 3), derived from reworked boulder-clay, shows an enrichment of tourmaline, garnet, kyanite, epidote, and amphiboles in the medium sand. Garnet shows a maximum in two non-successive sizes. An explanation of this fact may be that the unworn garnet is found in the 0.4–0.3 mm. fraction and garnet broken by surf action in the 0.2–0.1 mm. fraction.

A sand of the lower terrace of the Rhine River (Niederterrasse) (Table 4) shows concentrations of garnet and augite in the fine sand; in the very fine sand there are concentrations of zircon, rutile, kyanite, staurolite, amphiboles, and topaz. Garnet has the same frequency in both the medium and fine sands. In the case of this sediment, the explanation of the frequency distributions involves (in addition to sorting) two different sources for heavy minerals—from the Alps and from the mountains of the upper Rhine Basin.

Concentrations of tourmaline, augite, and garnet in medium sand, and of rutile and zircon in the fine and very fine sand have been found in the sands of the River Enz (northern Black Forest), derived from granite, Bunter sandstone, and upper Triassic (Keuper).

Sindowski (1939), from a study of about 100 samples of marine sand, found that tourmaline, garnet, staurolite, kyanite, andalusite, sillimanite, and titanite were concentrated in the fine sand (0.2–0.1 mm.) and that zircon and rutile are predominant in the very fine sand (0.1–0.5 mm). (See below, section 5a, for an additional, similar example.)

TABLE 4. *Rhine-sand of the lower terrace, South-west Germany*
(after W. Richter 1939)

Heavy minerals	0.5–0.2 mm.	0.2–0.1 mm.	0.1–0.05 mm.
tourmaline	1	—	2
zircon	—	1	10
rutile	1	1	4
garnet	30	30	10
kyanite	1	—	4
staurolite	—	2	3
epidote	1	1	2
amphiboles	1	7	18
augite	6	13	5
topaz	—	—	6
opaque	59	45	36

In heavy mineral suites, garnet is distinctly concentrated in the fraction 0.5–0.2 mm., and occasionally in the 0.2–0.1 mm. fraction, while the opaques (ores) predominate in the fraction 0.1–0.05 mm. (figure 2).

These examples show clearly that the choice of a single, narrowly-limited grain size may give a completely erroneous picture of the heavy mineral composition of a sediment. Some of the minerals present may appear to have zero frequency; others may seem to be much more or much less abundant than their true value. In the case of sands, the fraction 0.2–0.1 mm. generally gives good average values if the modal grain size lies in the 0.3–0.2 mm. fraction, but other fractions must be examined if greater exactness is required.

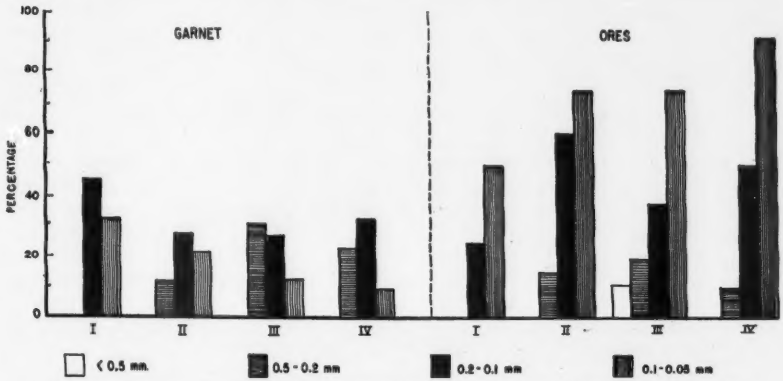

FIG. 2.—Histograms of the distribution of garnet and opaques (ores) in various size fractions of four samples from the coastal placers of Sleswick-Holstein.

4. RESISTANCE OF HEAVY MINERALS TO WEATHERING

In using heavy minerals to solve paleogeographical problems, it is essential to have information as to the stability of the various minerals (a) during transportation, and (b) after their deposition within the sediment.

(a) Up to the present there have been no satisfactory studies of stability during transportation. The uncleavable minerals such as garnet, rutile, zircon, and topaz are stable in transport. For example, there is a concentration of garnet in sediments transported for a long time or a long distance. Kyanite, sillimanite, and amphiboles are unstable, since they easily split into smaller and smaller fragments. Other species have values intermediate between these extremes.

(b) It is generally considered that tourmaline, zircon, and rutile are the only really stable heavy minerals. Paleozoic sandstones and greywackes of the Rhenish Schiefergebirge, Bunter sandstone, Eocene kaolin, and some soils contain only these three minerals, all others having been destroyed by weathering.

Olivine, apatite, glauconite, augite, and amphiboles weather readily (W. Richter, Sindowski, Zöbelein). In humid regions, garnet behaves similarly (Sindowski, Weyl, Zöbelein). On the other hand, W. Richter (1937) considers garnet to be a stable mineral, as he has shown in his study of the Cretaceous of the eastern Alps. All the other minerals have intermediate values of stability.

Weathering and destruction of heavy minerals takes place more rapidly in coarse and medium-sized sediments and

TABLE 5. *Resistance of heavy minerals to weathering*

Group	Resistance to weathering	Heavy minerals
VII	Not weatherable (stable)	Tourmaline, zircon, rutile
VI	Slightly weatherable	Kyanite, staurolite, sillimanite, dumortierite, corundum
V	Difficultly weatherable	Andalusite
IV	Rather difficultly weatherable	Titanite, brookite, anatase
III	Rather easily weatherable	Epidote, zoisite
II	Easily weatherable (unstable)	Garnet, amphiboles, augite
I	Very easily weatherable (unstable)	Apatite, olivine, glauconite

in those without calcareous content than in argillaceous, calcareous or loamy sediments. Garnet above all is easily etched and dissolved by carbon dioxide and humic acids. At first there are small etching-scars, and then the mineral breaks down into crescent-shaped fragments. Garnet is protected from weathering by a cover of overlying, younger deposits or by the presence of carbonate (Sindowski, Weyl).

In the examination of Paleozoic and Mesozoic heavy-mineral suites, one should always bear in mind the possibility that certain unstable mineral species have been partly or completely destroyed by weathering. Otherwise, paleogeographical interpretations may be completely erroneous.

Following Neumaier, Sindowski, Weyl, and Zöbelein, heavy minerals can be divided in the manner shown below, according to their resistance to weathering. This list is by no means a final one, and it would be desirable to have it supplemented by the experiences of other sedimentary petrologists.

TABLE 6. *Weathering of dune sands, East Prussia, showing average percentages of important heavy minerals* (after Dechend 1937)

Heavy minerals	white dunes	yellow dunes	brown dunes
garnet	35	28	22
epidote	5	7	8
amphiboles	15	39	48
apatite	3	5	7
glauconite	27	7	—

Specific cases of heavy-mineral weathering are given in the text and tables below. The dune sands are derived from lower Oligocene glauconitic sands (with amber) and from boulder-clay. Opaque minerals (not shown in the table) and glauconite are more or less completely destroyed by weathering and garnet shows a significant decrease. Although the amphi-

TABLE 7. *Kaolin sands on Bunter sandstone, southwest Germany* (after W. Richter and Sindowski)

	1	2	3	4
tourmaline	57	61	13	20
zircon	27	22	71	70
rutile	3	9	11	10
anatase	1	8	—	—
garnet	6	—	3	—
staurolite	1	—	—	—
kyanite	1	—	—	—
amphiboles	3	—	2	—
augite	1	—	—	—

1. Bunter sandstone, Black Forest
2. Kaolin sand, Pliocene, Black Forest
3. Bunter sandstone, Odenwald
4. Kaolin sand, Pliocene, Odenwald

TABLE 8. *Eocene kaolin on Devonian clayslate, Rhenish Schiefergebirge* (after Sindowski 1938)

Heavy minerals	Devonian	Eocene kaolin
tourmaline	14	26
zircon	60	58
rutile	5	16
staurolite	9	—
kyanite	7	—
andalusite	1	—
epidote	1	—
amphiboles	2	—

boles and apatite are easily weatherable, they show a relative increase in frequency in the highly weathered, brown dunes.

The two following examples show the weathering of heavy minerals as a result of kaolin-forming processes. During the Pliocene, the Bunter sandstone of the Odenwald and Black Forest was exposed, and its surface was weathered to kaolin, with little or no reworking of materials. During this weathering only the stable minerals zircon, tourmaline, and rutile survived.

In the Rhenish Schiefergebirge, the kaolin is weathered Devonian clayslate, and the original stratification is still preserved.

Sindowski (1940) has described a remarkable example of heavy-mineral weathering in the Pleistocene terraces of the Rhine. The terrace sediments without cover of younger deposits (for example, loess) show a more intensive weathering than those with overlying deposits. Weathering of the sediments of the upper terrace (Hauptterrasse) and the middle terrace (Mittelterrasse) has brought about a decrease in the amount of garnet and augite, and a relative increase of epidote and amphiboles.

The examples in Tables 6 and 9 show clearly that under humid conditions, especially, garnet is corroded and weathered, while the amphiboles are not affected. All heavy minerals except the stable ones (tourmaline, zircon, rutile) are corroded and destroyed by kaolin-forming and laterite-forming processes.

The heavy minerals in any sediment are, in a sense, the survivors of selective weathering. The intensity of selection becomes greater and greater with the age of the sediment and with the length of time it has been exposed at the surface.

5. RECENT

(a) *Modern beach sands of the Baltic and North Sea*

Several workers have described the mineral suites of beach sands, particularly from modern mineral concentrates or placers (Seifen). The concentration of heavy minerals in the coastal placers is quite variable. Ore placers and ore-garnet placers are by far the most common. Glacial sands are the source of the heavy minerals.

Weyl (1937) studied the coastal placers of the Sleswick-Holstein coast of the Baltic Sea, separating the heavy minerals into the following fractions: greater than

TABLE 9. *Heavy mineral composition of the upper and middle terraces of the lower Rhine* (after Sindowski 1940)

	1	2	3	4
garnet	18	7	15	10
epidote	18	38	14	20
amphiboles	9	10	11	19
augite	5	6	45	27

1. Upper terrace with younger cover
2. Upper terrace without younger cover
3. Middle terrace with younger cover
4. Middle terrace without younger cover

TABLE 10. *Mineral composition of coastal placers, Frisian Islands* (after Lamcke)

Locality	Light mins.	Garnet	Opaque
Borkum	67	21	12
Juist	64	15	21
Norderney	20	33	47
Baltrum	33	19	48
Langeoog	64	11	25
Spiekeroog	72	6	22
Wangeroog	78	5	17

0.5 mm., 0.5–0.4, 0.4–0.3, 0.3–0.2, 0.2–0.1, and 0.1–0.05 mm. He classified the placers as ore, ore and garnet, and garnet placers. Garnet is concentrated chiefly in the fraction 0.3–0.2 mm., rarely in 0.4–0.3 mm. The ores appear in the 0.2–0.1 mm. fraction and rarely in the 0.1–0.05. The other heavy minerals (only zircon in most cases) occur chiefly in the 0.1–0.05 mm fraction.

The ores are 50% or more ilmenite, the rest magnetite. The other heavy minerals include: tourmaline, zircon, rutile, staurolite, kyanite, amphiboles, augite, and epidote. Boulder-clay is the source of the beach sands and placers.

The coastal placers in the Warnemuende region are formed by wave action on the seaward slope of an offshore bar. Engelhardt (1938) studied these placers intensively, and he found that the quantity of heavy minerals concentrated in placers was a function of the beach slope.

Sindowski (1938) studied both the beach sands and the coastal deposits near Warnemuende (boulder-clay, glacial sands, dunes) from which the beach sands are derived. Because of the eastward currents and drift, the beach sands are rather uniform in mechanical composition and quantity of heavy minerals. The coefficient r^2 calculated according to the formula of Dryden varies between 0.8 and 0.9. The heavy minerals are derived from the boulder-clay. The boulder-clay is the ultimate source for all the other deposits, and at each reworking of materials there is a concentration of garnet, particularly well shown in the dune and beach sands.

Kleinsorge (1937) studied the seasands around Heligoland. He found 60% of garnet in the medium sands and only 38% in the fine and very fine fractions. All other heavy minerals are predominant in the 0.2–0.02 mm. fraction.

TABLE 11. *Mineral composition of coastal placers, Sleswick-Holstein* (after Weyl 1937)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Ores (opaque)	86	83	77	69	57	76	40	59	57	48	47	36	31	14
Garnet	2	7	17	20	28	18	22	22	23	27	13	22	46	26
Heavy minerals	9	8	4	6	9	2	2	6	7	7	5	13	8	6
Light minerals	3	2	2	5	6	4	36	13	13	18	35	29	15	54

1–6. modern ore placers; 7–12. modern ore and garnet placers; 13. modern garnet placer; 14. modern eolian concentrate.

TABLE 12. *Concentration in beach placers* (after Engelhardt 1938)

Slope of beach	Concentration
Smaller than 5 deg.	No concentrate
6–9	Some concentrate
10–11	Average quantity of concentrate
12–14	Large quantity of concentrate
Greater than 14 deg.	Greatest quantity of concentrate

TABLE 13. *Mineral composition of beach sands and coastal deposits, Mecklenburgh, showing average values for the important heavy minerals* (after Sindowski 1938)

Heavy minerals	boulder-clay	glacial sand	dune sand	beach sand
Garnet	28	31	44	46
Epidote	7	10	6	6
Amphiboles	21	18	12	15
Augite	5	2	5	3
Olivine	2	1	1	1

(b) *Modern river sands*

Erberich (1937) examined the modern sands of the Rhine between Mayence and the Dutch border, and found that several associations of heavy minerals may be recognized. The Alpine assemblage consists of garnet, epidote, and amphiboles. From the mountains along the Rhine come tourmaline, zircon, rutile, kyanite, and staurolite, and the volcanic areas yield augite, basaltic hornblende, and titanite. Based on the volcanic heavy minerals, the Rhine course is divided into four zones:

Zone A: from Ruedesheim to Boppard, with some augite, basaltic hornblende, and titanite

Zone B: from Weissenthrum to Kripp, with a great quantity of augite, basaltic hornblende, and titanite

Zone C: from Mehlem to Laengst, with some augite, basaltic hornblende, and titanite

Zone D: from Uerdingen to Emmerich, with a great quantity of augite, basaltic hornblende, and titanite.

The great concentration of augite in Zone D is remarkable since its source lies not far upstream, in the southern part of Zone C. A similar enrichment was found in the lower course of the Enz River in the northern Black Forest. (Further remarks on Rhine sands will be found under Pleistocene terraces, below.)

Kleinsorge (1937) studied the heavy minerals of the fractions 0.5–0.2 mm. and 0.2–0.02 mm. of the Enz River in the northern Black Forest (figure 3). The source of the minerals of samples 1–2 is the Bunter sandstone, of samples 3–11 the Bunter sandstone and granite, and of samples 14–24 the upper Triassic (Keuper). Kleinsorge concluded from the curves for hornblende in the fractions 0.5–0.2 mm. and 0.2–0.02 mm. that the amphiboles are reduced in size during transportation, and that from sample 14 on, they are being concentrated in the 0.2–0.02 mm. fraction. Augite shows a frequency of 90% in both fractions of samples 23 and 24. Kleinsorge explains this increase by assuming the existence

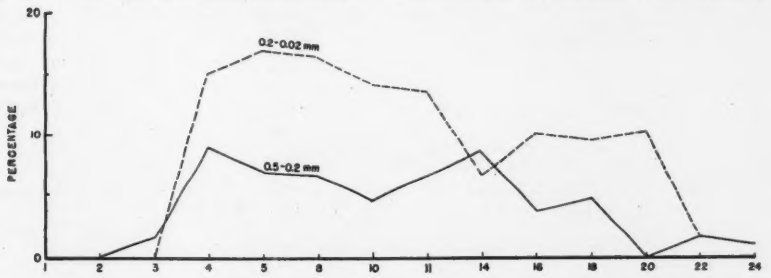

FIG. 3.—Distribution curves for hornblende in the 0.5–0.2 mm. and 0.2–0.02 mm. fractions, sediments of the Enz River, northern Black Forest. Numbers along the abscissa are sample-numbers; lower numbers are upstream, higher numbers downstream (after Kleinsorge).

TABLE 14. *Mineral composition of the Pleistocene terraces of the Rhine River, showing average values for the important heavy minerals* (after Sindowski 1939)

	1	2	3	4	5	6	7
Garnet	32	44	27	13	11	25	26
Epidote	17	3	4	19	14	12	12
Hornblende	17	25	8	7	11	17	18
Augite	1	—	—	11	28	23	27

1. Clay of Jockgrim, Palatinate
2. Sand of Mosbach, near Mayence
3. Clay of Tegelen, Lower Rhine basin
4. Upper terrace
5. Middle terrace
6. Lower terrace
7. Modern Rhine sand, after Erberich (1937)

of a volcanic source between samples 20 and 22, but it may well be that the rather sudden rise in frequency is due to effects of sorting. This latter explanation is borne out by rather high frequencies of augite in the lower course of the Rhine, far from any volcanic source.

6. PLEISTOCENE (*glacial*)

(a) *Terraces of the Rhine River*

The glacial terraces of the middle and lower Rhine were studied intensively by Sindowski (1940). He found that the most common heavy mineral assemblage, consisting of garnet, hornblende, and epidote primarily, was derived from the Alps—the alpine assemblage (alpine Schüttung) of Sindowski (1939). In the middle terrace there is also an assemblage of volcanic minerals (augite, basaltic hornblende, and titanite) which Sindowski called the Eifel assemblage. Metamorphic minerals admixed with these two assemblages were derived principally from the Rhenish Schiefergebirge; this metamorphic suite was named the Devonian assemblage by Sindowski (1939). Epidote, the metamorphic and the stable minerals increase in frequency from the modern sands to the upper terrace, while garnet, hornblende and augite decrease. This is a result largely of selective weathering, rather than of changing conditions of sedimentation.

(b) *Loess of the middle and lower Rhine region*

The loesses on the Pleistocene terraces of the Rhine have been derived from the terrace sands. Their mineral composition is more similar to that of the middle terrace than of the upper. The younger loesses generally have a higher content of augite and a lower content of hornblende than do the older ones.

Examination of the loess of lower Bavaria (Zöbelein 1940) shows a great preponderance of Alpine minerals. Garnet and hornblende decrease in frequency during soil formation on the loess, whereas eipdote increases in the same manner as in the terraces of the Rhine.

(c) *Boulder-clays of north Germany*

The Fennoscandian assemblage (Schüttung) of heavy minerals can be distinctly recognized in the Pleistocene boulder-clays. This assemblage can be divided into a Finnish suite in eastern Germany and a Scandinavian suite in northern and northwestern Germany. The Finnish suite is marked by its content of augite

TABLE 15. *Mineral composition of the loesses of the lower Rhine, showing average values for the important heavy minerals* (after Sindowski 1940)

	1	2	3	4	5	6	7
Garnet	22	9	9	5	5	14	28
Epidote	—	9	10	7	1	14	7
Hornblende	9	15	11	8	4	6	4
Augite	—	39	44	41	76	24	9

1. Oldest loess, Rhine Hassia
2. Older loess, near Coblentz
3. Younger loess, near Coblentz
4. Older loess, near Coblentz
5. Younger loess, near Coblentz
6. Older loess, near Cologne
7. Younger loess, near Cologne

TABLE 16. *Mineral composition of the loess and loess soil of lower Bavaria, showing average frequencies of Alpine heavy minerals* (after Zöbelein)

Heavy minerals	Loess	Loess soil
Garnet	19	11
Epidote	33	49
Hornblende	14	10

in East Prussia. An increase of epidote from younger boulder-clay 4. to oldest clay 7. is clearly seen in samples 4. to 7. from Mecklenburgh, while the garnet shows a decrease. Similar changes in frequencies have already been pointed out for the Pleistocene Rhine terraces and for the loess and loess soils of Bavaria.

(d) *Volcanic tuffs of the Lake of Laach, Eifel*

The heavy mineral suites of the volcanic tuffs of the Lake of Laach consist principally of basaltic hornblende, augite, and titanite, together with some non-volcanic minerals from adjacent rocks. These figures clearly show how difficult it is to distinguish between basic and acid tuffs by this method. Even the loesses, lying on or between the tuffs, cannot be differentiated by heavy mineral analysis.

7. TERTIARY

(a) *Pliocene*

Kaolin sands, residual sands and gravels, and river sands form the majority of the Pliocene deposits of Germany. The kaolin sands of the Black Forest and the Odenwald have already been discussed (section 3. of this paper). The kaolin sands of Table 19 were derived ultimately from weathered Bunter sandstone, then reworked and deposited by rivers. The arenaceous deposits of Freinsheim in the Palatinate also received contributions from the lower Per-

TABLE 17. *Mineral composition of boulder-clays of north Germany, showing average frequencies of heavy minerals derived from Fennoscandia* (after Fiedler, W. Richter, Sindowski, Steinert)

	1	2	3	4	5	6	7	8	9	10
Garnet	28	21	28	26	35	23	14	25	27	20
Epidote	5	3	7	10	17	20	31	3	11	18
Hornblende	20	17	21	56	41	50	47	58	54	40
Augite	14	13	5	—	—	—	—	—	—	3
Olivine	1	—	2	+	—	+	1	10	2	+

1. Older boulder-clay, East Prussia
2. Younger boulder-clay, East Prussia
3. Boulder-clay, Mecklenburgh
4. Boulder-clay of the Pommerian glacial stage, Mecklenburgh
5. Boulder-clay of the Posnian glacial stage, Mecklenburgh
6. Boulder-clay older than 5, Mecklenburgh
7. Boulder-clay of the Elster glacial stage, Mecklenburgh
8. Boulder clay, older than the Pommeranian glacial stage, Mecklenburgh
9. Boulder-clay older than the Posnian glacial stage, Mecklenburgh
10. Boulder-clay, Sleswick-Holstein

TABLE 18. *Mineral composition of volcanic tuffs of the Lake of Laach, showing average values for volcanic minerals* (after Sindowski 1938)

	1	2	3	4	5	6	7
Augite	40	46	27	45	46	33	43
Hornblende	10	6	4	5	4	5	7
Titanite	7	5	7	12	5	10	2

1. Basaltic tuff
2. Tuff of Glees
3. Tuff of Kahlenberg
4. Tuff of Huettenberg
5. White pumice tuff
6. Gray trachyte tuff
7. Younger loess, for comparison

mian (Rothliegende). In the Rhineland, the river sands and gravels with silicified oolites (Kieseloolith) represent Pliocene river sands of the Rhine. At that time, the Rhine was getting no sediments from the Alps, but was carrying principally weathering-debris from the Rhenish Schiefergebirge; this source area consists chiefly of Devonian rocks and of the Bunter sandstone. The mineral suites of these river deposits (which will be described with the Tertiary of the lower Rhine basin) contain essentially stable minerals like those of the Devonian and the Bunter sandstone. Garnet and hornblende, less stable, are rare, and are found only in the 0.1–0.05 mm. fraction.

TABLE 19. *Mineral composition of Pliocene kaolin sands of south-west Germany, showing average values of the important minerals* (after Sindowski 1938)

	1	2	3	4	5
Tourmaline	18	56	43	20	34
Zircon	49	15	11	70	36
Rutile	14	9	1	9	8
Garnet	3	6	4	1	3
Staurolite	2	—	1	—	1
Kyanite	3	—	1	—	1
Hornblende	1	2	3	1	1
Augite	—	3	—	—	—
Titanite	3	1	—	—	1

1. Kaolin gravel, southern Black Forest
2. Kaolin sand, Palatinate
3. Deposits of Freinsheim, Palatinate
4. Kaolin sand, Odenwald
5. Average value for the Pliocene

TABLE 20. *Mineral composition of the marine middle Miocene of northwest Germany, showing average values for minerals of the Fennoscandian assemblage* (after Sindowski, and Rohling)

	1	2	3	4
Garnet	13	35	12	16
Epidote	14	13	26	2
Hornblende	18	20	21	2

1. Vechta, Oldenburgh
2. Nordlohne, Oldenburgh
3. Bersenbrueck, Westfalia
4. Straelen, Nether Rhine

(b) *Miocene*

The marine middle Miocene (Helvetian) of north Germany was deposited in a bay of the Miocene North Sea. Its heavy minerals were derived from Fennoscandia and from the mountains of central Germany (principally the Rhenish massif). A decrease in the proportion of the Fennoscandian assemblage toward the south and southwest can be clearly seen: the three principal minerals decrease in frequency from 70–75% in Sleswick-Holstein, to 60% in Oldenburgh, and to 20% along the lower Rhine.

The marine middle Miocene and brackish Miocene in lower Bavaria contain heavy minerals derived from the Alpine provenance, but the overlying terrestrial upper Miocene has a completely different mineral content in that it lacks the principal Alpine minerals garnet, epidote and hornblende. The separation of marine and brackish Miocene is difficult since both were deposited under similar conditions. In the marine deposits, the content of epidote and hornblende is a little greater, and in the brackish Miocene there is a higher frequency of tourmaline and rutile.

As in Bavaria, there are also Miocene river sands in the lower Rhine region. In this area a Miocene Rhine laid down thick, coarse and medium sands—the deposits of Fischbach—derived in large part from the Triassic of the Eifel. The mineralogy of these deposits will be taken up with the lower Rhenish Tertiary, but in general their high content of garnet and the presence of picotite serve to differentiate these sands from the overlying Pliocene

TABLE 21. *Mineral composition of the Miocene of lower Bavaria, showing average values of the important heavy minerals* (after Neumaier and Zöbelein)

	T	Z	R	G	S	K	E	A	
Upper Miocene	16	8	19	1	38	18	—	—	Sheet Pfarrkirchen
	19	4	14	—	37	26	—	—	Sheet Birnbach
River sands	14	3	14	1	47	19	—	—	Sheet Griesbach
Brackish	7	1	5	17	3	3	47	17	Sheet Pfarrkirchen
	6	+	1	19	6	2	37	25	Sheet Birnbach
Miocene	5	+	2	17	4	—	54	16	Sheet Griesbach
Marine	2	1	1	15	1	1	54	24	Sheet Pfarrkirchen
Middle	4	2	1	13	4	1	48	26	Sheet Birnbach
Miocene	4	2	+	21	3	+	48	19	Sheet Griesbach

T = Tourmaline; Z = Zircon; R = Rutile; G = Garnet
S = Staurolite; K = Kyanite; E = Epidote; A = Amphiboles

river sands. The picotite was derived ultimately from the Cambro-silurian of the Hohes Venn. From this source it was carried into the Triassic rocks of the north Eifel, and from the erosion of these rocks it has been deposited in the Fischbach sands. Silicified and kaolin sands in the Miocene of lower Bavaria and of the lower Rhine basin prove intensive terrestrial weathering at that time.

(c) *Oligocene*

The Oligocene in the lower Rhine basin begins with terrestrial gravels and sands, changing upward to middle Oligocene fine sands and clays in the northern part of the basin. Overlying are a series of marine fine sands of the upper Oligocene. The lower brown-coal sands are partly marine, grading into river sands; to the south, these sandy beds grade into clay. A bed of brown coal 100 meters thick lies between the lower and upper brown-coal sands. These upper brown-coal sands are very similar to the Miocene in mineral content, particularly in the presence of a significant amount of garnet.

As can be seen from the table above,

TABLE 22. *Mineral composition of the Nether Rhenish Tertiary, showing average values of the important heavy minerals* (after Sindowski 1939)

	T	Z	R	G	S	K	E	A	t
Upper Rhine terrace	12	12	4	13	10	6	19	7	1
Pliocene river sands	35	32	6	2	9	3	1	1	2
Marine middle Miocene	44	13	8	16	7	5	1	2	—
Miocene Fischbach deposits	30	22	5	19	9	4	1	+	2
Upper brown-coal sands	27	28	11	5	6	10	3	2	2
Brown coal (100 m.)									
Lower brown-coal sands	30	22	14	+	9	11	2	+	1
Marine upper Oligocene	28	24	10	1	4	20	—	2	—
Marine middle Oligocene	23	35	8	10	3	14	—	+	—
Terrestrial old Oligocene	12	50	19	3	5	5	1	1	4
Kaolin sand and clay	15	65	20	—	—	—	—	—	—

T = Tourmaline; Z = Zircon; R = Rutile; G = Garnet; S = Staurolite; K = Kyanite; E = Epidote; A = Amphiboles; t = Titanite

the following pairs of deposits—either in contact or separated by comparatively small stratigraphic interval—can be differentiated by heavy mineral analysis: the upper Pliocene and older Pleistocene terrace; the upper brown-coal sands and the Fischbach deposits; the marine upper Oligocene and marine middle Oligocene; and finally the (Eocene) kaolin sand and terrestrial Oligocene. It can also be seen that the terrestrial Oligocene is made up in considerable part of reworked Eocene kaolin sand. The influence of the high Oligocene is represented by the *Cyrena* marls.

In the Mayence basin, the marine sands of Mayence and the septaria clay can be easily differentiated by heavy-mineral analysis. The Mayence sands were derived largely from local sources, but by the time the septaria clays were deposited there was an influx of Fennoscandian minerals, showing more distant sources of supply. The Fennoscandian influence gradually dies out after the *Cyrena* marls. These marls, in turn, can

TABLE 23. *Mineral composition of the Tertiary of the Mayence basin, showing average values of the important heavy minerals* (after Weyl 1938; converted to percentages)

	T	Z	R	G	S	K	E	A	a
Fresh-water Miocene	15	21	—	13	7	2	3	—	5
Cyrena marls	12	5	1	18	5	1	12	4	8
Schleich sands	12	4	+	22	7	4	16	13	5
Septaria clays	12	4	1	30	12	4	10	9	11
Marine sand of Mayence D	7	3	+	2	—	—	—	—	1
Marine sand of Mayence C	60	12	3	4	—	—	—	1	—
Marine sand of Mayence B	28	4	1	3	—	—	—	—	49
Marine sand of Mayence A	74	8	1	1	—	—	—	—	—

Marine sand of Mayence: A from Bunter sandstone; B from melaphyre; C from lower Permian; D from quartz porphyry.

T = Tourmaline; Z = Zircon; R = Rutile; G = Garnet; S = Staurolite; K = Kyanite; E = Epidote; A = Amphiboles; a = Augite.

zircon content in the Eocene sand is apparent as far up as the marine middle Oligocene. From the upper Oligocene to the upper Pliocene the percentage of tourmaline is greater than that of zircon.

The Oligocene differs from the Miocene in that its content of kyanite is greater than that of staurolite, and by its small content of garnet. The marine upper Oligocene can be differentiated from the overlying lower brown-coal sands by its high content of kyanite and its small content of staurolite, by the appearance of sillimanite, and by the absence of epidote.

In the Mayence basin the marine sands of Mayence (Mainzer Meeressand) form the lower part of the middle Oligocene, and are overlain by the septarian clays (Septarienton) and the Schleich sands (Schleisande). The upper be separated from the overlying Miocene by their heavy-mineral content.

In the upper Bavarian basin of the Molasse, the middle Oligocene begins with the lower marine Molasse; above are a series of brackish and fresh-water formations, including one marine horizon, the Promberg sand. The lower marine Molasse and the horizon of quarrystones (Bausteinzone) can be separated by heavy minerals since the former has almost equal proportions of tourmaline and garnet, the latter a much higher proportion of garnet. The overlying brackish and fresh-water deposits are quite similar in heavy-mineral content. The Promberg marine sands are slightly different in mineral composition.

It is rather remarkable that of the principal Alpine minerals—garnet, horn-

TABLE 24. *Mineral composition of the middle Oligocene Molasse of upper Bavaria, showing average values of the important heavy minerals* (after Andrée 1936)

	T	Z	R	G	S	K
Upper colored Molasse	9	15	6	61	7	1
Promberg deposits	10	20	9	58	3	—
Cyrena marls	7	11	5	65	11	1
Lower colored Molasse	8	3	7	66	16	—
Zone of quarrystones	15	9	9	62	5	—
Lower marine Molasse	38	15	7	36	3	—

T = Tourmaline; Z = Zircon; R = Rutile; G = Garnet; S = Staurolite; K = Kyanite.

blende, and epidote—only garnet is at all abundant in the middle Oligocene of the upper Bavarian Molasse. Andrée believes that metamorphic rocks to the south yielded the sediments which poured into the middle-Oligocene Molasse geosyncline. But it is not known whether the epidote and hornblende from these rocks were destroyed in transportation or by weathering.

The influence of the Fennoscandian source is clearly shown in the middle Oligocene of northern Germany. The principal minerals from this source are garnet, hornblende, and epidote. Toward the south and southwest, away from the source, there is a relative increase in the frequency of garnet, and a decrease in hornblende and epidote. This change in proportions is attributed to the greater resistance of garnet in transportation.

The lower Oligocene of the Samland in East Prussia is represented by the famous marine glauconitic sands containing amber. These sands, also, show the influence of the Fennoscandian source, particularly the Finnish, as is shown by their content of augite.

(d) *Eocene and Paleocene*

The Eocene of north Germany consists almost solely of clays, although there are several thin beds of volcanic tuff in lower Eocene I. Most of the clay is reworked Chalk and upper Cretaceous, although the heavy minerals show that there have been contributions from the Fennoscandian distributive province. The slight differences in heavy-mineral composition are to be explained as due to the uniform conditions of sedimentation.

TABLE 25. *Mineral composition of the north German middle Oligocene, showing average values of the principal minerals of the Fennoscandian assemblage* (after Sindowski 1948)

	1	2	3	4
Garnet	8	8	11	16
Hornblende	48	4	1	1
Epidote	17	10	1	+

1. Middle Oligocene, Stettin, Pomerania
2. Middle Oligocene, Oldenburgh
3. Middle Oligocene, Mülheim on Ruhr
4. Middle Oligocene, near Cologne

(e) *Quantity of heavy minerals in the Tertiary*

The extent to which the quantity of

TABLE 26. *Mineral composition of the East Prussian lower Oligocene* (after W. Richter 1937)

Tourmaline	13
Zircon	51
Rutile	14
Garnet	3
Staurolite	2
Kyanite	3
Epidote	1
Hornblende	2
Augite	8

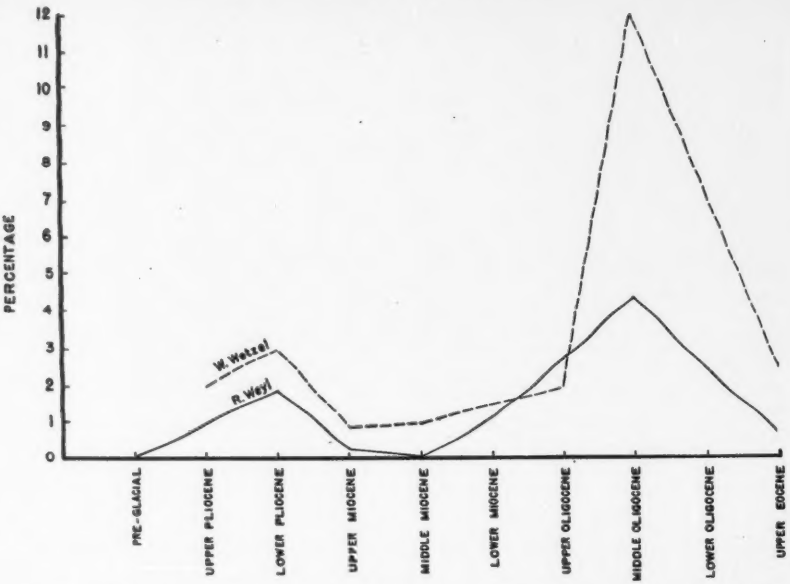

FIG. 4.—Curves showing the quantity of heavy minerals in the European Tertiary (after Weyl and Wetzel).

heavy minerals may be characteristic of a certain horizon is a question which has received but little investigation. Weyl (1932) constructed a curve for the quantities in the north German Tertiary (figure 4), and he found a large maximum in the middle Oligocene and a lesser maximum in the lower Pliocene. Wetzel reports similar figures for the rocks of the Roumanian Tertiary. Although these two workers agree, their results are scarcely sufficient for any generalization. If other workers will consider this problem it may be possible to determine whether the variation in heavy mineral content is a function of climatic change—as Weyl and Wetzel believe—or is to be attributed to uplift and erosion.

8. CRETACEOUS

Deecke (1935) distinguishes three distributive provinces which have contrib-

TABLE 27. *Mineral composition of the south Oldenburghian Paleocene and Eocene, showing average values of the important heavy minerals* (after Rohling 1941)

	1	2	3	4	5
Tourmaline	39	35	30	44	29
Zircon	25	17	24	12	26
Rutile	5	5	3	4	2
Garnet	6	13	6	4	7
Staurolite	7	5	7	10	16
Kyanite	7	7	19	19	12
Epidote	4	6	3	+	2
Hornblende	3	7	2	1	3

1. Paleocene
2. Base of lower Eocene I
3. Lower Eocene I
4. Lower Eocene II
5. Lower Eocene III

TABLE 28. *Mineral composition of the northwest German lower Cretaceous, showing the average values* (after Deecke 1935)

	1	2	3	4	5
Tourmaline	29	23	33	32	—
Zircon	53	56	50	58	—
Rutile	12	6	14	10	—
Garnet	1	10	+	+	7
Staurolite	2	2	3	+	2
Kyanite	3	3	+	—	1

1 Wealden
2. Valangian
3. Lower Albian
4. Lower Cretaceous sandstones
5. Maastrichtian

uted to the north German lower Cretaceous. In the northeast there is a massif north of the Aller River, from which zircon, tourmaline, rutile, kyanite, staurolite, garnet, and small amounts of augite and hornblende were derived. This massif is probably part of the Pompeckyan uplift (Pompecky'sche Schwelle), and its minerals belong to the Fennoscandian assemblage. In the southeast and south are the Triassic rocks of the Hercynian massif, furnishing zircon, tourmaline, rutile, and rarely kyanite, staurolite, and garnet. In the southwest, the Rhenish massif furnished zircon, tourmaline, rutile, and small amounts of garnet, hornblende, and staurolite.

There has been comparatively little work on the Cretaceous heavy minerals since it is seldom encountered except in borings. So far, there has been no attempt to differentiate the various Cretaceous horizons by heavy-mineral analysis.

9. JURASSIC

Deecke (1935) has also distinguished three distributive provinces for the Jurassic rocks of northwest Germany. In the northeast there is the same massif near the Aller River. In the southeast, the Bunter sandstones of the Flechting Hills furnished zircon, tourmaline, and rutile, and in the northwest the Frisian massif furnished zircon, rutile, and tourmaline. The very high content of zircon and the unusually high content of rutile are characteristic of the Jurassic rocks. So far, samples are few, and mostly from boreholes, so that individual horizons cannot be differentiated by heavy-mineral analysis.

TABLE 29. *Mineral composition of the northwest German Jurassic, showing the average values* (after Deecke 1935)

	1	2	3	4	5
Tourmaline	30	11	6	11	10
Zircon	46	57	68	65	67
Rutile	16	19	14	18	23
Garnet	2	4	5	3	—
Staurolite	4	1	3	1	—
Kyanite	2	1	4	2	—
Hornblende	—	6	—	—	—
Augite	—	1	—	—	—

1. *Polyplocus* sandstone
2. Cornbrash
3. *Macrocephalus* sandstone
4. Upper Oxfordian
5. Lower Kimmeridge

The Jurassic rocks of the western slope of the Black Forest were derived from the crystalline rocks of that area, as was shown by Sindowski's (1936) investigations of the Dogger sandstones.

TABLE 30. *Mineral composition of the southwest German Dogger sandstone, showing average values* (after Sindowski 1936)

Tourmaline	25
Zircon	20
Rutile	3
Garnet	36
Kyanite	3
Hornblende	3
Biotite	8

TABLE 31. *Mineral composition of the north Eifel Triassic, showing average values* (after Sindowski 1939)

Heavy minerals	Bunter sandstone	Muschelkalk	Keuper sandstone
Tourmaline	33	51	11
Zircon	36	19	55
Rutile	7	3	11
Anatase	2	—	1
Garnet	6	14	—
Staurolite	2	3	4
Kyanite	8	2	5
Hornblende	1	—	2
Augite	—	—	2
Titanite	2	—	—
Picotite	+	—	2

10. TRIASSIC

The three formations of the Triassic in the north Eifel can be differentiated by heavy-mineral analysis. The Muschelkalk sandstone is characterized by its extremely high content of tourmaline, a high content of garnet, and a low content of zircon. In the Keuper, there is a high proportion of zircon, and tourmaline and rutile have about the same frequency; picotite also forms a conspicuous element.

The heavy minerals of these rocks of the north Eifel have been derived primarily from the lower Devonian of the Rhenish Schiefergebirge and the Cambro-silurian of the Hohes Venn. Garnet and picotite, in particular, have been derived from the Hohes Venn.

Other studies of the Bunter sandstone, in southwestern and northwestern Germany, show that the characteristic minerals are the stable species tourmaline, zircon, and rutile; all others are rare or completely absent. An explanation of this restricted suite is to be found in the fact that the Bunter is made up largely of reworked lower Permian (Rothliegende).

The Bunter sandstone of Heligoland Island and of Sleswick-Holstein differs from the southwest German Bunter in its high content of garnet. In the Fennoscandian assemblage, from which it was derived in this case, garnet is the mineral most resistant to transportation.

11. PERMIAN

The lower Permian (Rothliegende) represents a series of deposits laid down under continental conditions, with intensive weathering. The weathering is shown by the heavy-mineral content in the various districts of Germany: though the sediments were derived, at least in part, from crystalline rocks, only the stable minerals tourmaline, zircon, and rutile remain. It is worthy of note that there is

TABLE 32. *Mineral composition of the Bunter sandstone, showing the average values* (after Kleinsorge, W. Richter, Sindowski, and Weyl)

	1	2	3	4	5	6	7	
Tourmaline	33	57	6	13	90	14	18	1–2. Northern Black Forest
Zircon	57	26	60	71	10	24	37	3. Heidelberg
Rutile	9	3	20	11	—	5	10	4. Odenwald
Garnet	—	6	—	3	—	57	33	5. Palatinate Forest
Staurolite	—	1	—	—	—	—	—	6. Heligoland Island
Kyanite	—	1	—	—	—	+	—	7. Eiderstedt, Sleswick
Hornblende	1	1	—	2	—	—	—	
Augite	—	1	—	—	—	—	—	

TABLE 33. *Mineral composition of the Permian, showing average values* (after Kleinsorge)

	1	2	3	4
Tourmaline	25	9	24	23
Zircon	60	78	61	65
Rutile	11	13	14	10
Staurolite	2	3	—	—
Kyanite	1	—	1	1
Zoisite	—	—	—	1
Hornblende	1	—	—	—

1. Northern Black Forest, Rothliegende
2. Hills of Flechting, Rothliegende
3. Sleswick-Holstein, Rothliegende
4. Sleswick-Holstein, Zechstein

an extreme enrichment of zircon in heavy-mineral suites that have been subjected to rigorous weathering.

12. DEVONIAN

The Devonian in northern Germany is represented by the terrestrial Old Red Sandstone. In Sleswick-Holstein, this sandstone received contributions from the Fennoscandian province, but in contrast, the Devonian of the Rhenish Schefergebirge contains only the stable minerals tourmaline, zircon, and rutile. Possibly there was further weathering of the heavy minerals after their deposition, since the clay-slates and limestones contain small quantities of several additional species.

13. SOURCES OF SEDIMENTARY MATERIALS (*Liefergebiete*)

The crystalline rocks of the Fennoscandian massif are the most important source for the heavy minerals of northern Germany. The most typical of these minerals are garnet, hornblende, augite, and epidote. From the Mesozoic on, the Fennoscandian assemblages can be divided into a Finnish assemblage with garnet, hornblende, and augite, and a western Scandinavian assemblage with garnet, hornblende, and epidote.

Based on heavy-mineral analysis, the influence of the Fennoscandian province is seen first in the Devonian of Norway and Sleswick-Holstein. Later, it can be followed in the Bunter sandstone of Heligoland, the Dogger of Pommerania, Jurassic of Hanover, Wealden of Pommerania, and in the lower Cretaceous of Pommerania, Mecklenburgh, and Hanover. The upper Cretaceous of Hanover also shows the influence of this province, but the Paleocene and Eocene of Oldenburgh seem not to have been derived from this source. In the lower Oligocene of Samland the Finnish sub-province contributed augite to the sediments. With the transgression of the Septaria clay, Fennoscandian minerals reach as far as the Mayence basin and the basin of the lower Rhine. The same assemblage is also present in the middle Oligocene of Oldenburgh, in the Stettin sands of Pommerania, and in the middle Oligocene of

TABLE 34. *Mineral composition of the north German Devonian deposits, showing average values* (after Kleinsorge, and Sindowski)

	1	2	3	4	5
Tourmaline	13	24	8	10	12
Zircon	44	55	80	42	38
Rutile	6	18	6	7	11
Garnet	27	—	3	3	8
Staurolite	5	—	2	5	2
Kyanite	3	2	1	7	15
Andalusite	—	1	—	2	1
Hornblende	—	—	—	9	8
Augite	1	—	—	—	—

1. Old Red Sandstone, Sleswick-Holstein
2. Greywacke, Lower Devonian, Eifel
3. Sandstone, Lower Devonian, Eifel
4. Clay-slate, Lower Devonian, Eifel
5. Limestone, Middle Devonian, Eifel

Leipsig. In the middle Miocene (Helvetian) transgression, Fennoscandian minerals spread over the whole marine basin, as far north as Holland. Among younger rocks, the terrestrial upper Miocene and Pliocene have not yet been studied for their heavy-mineral content, but the presence of blue quartz and blue hornstone in these sands makes a Fennoscandian source likely. During the Pleistocene glaciation the whole of north Germany received sedimentary materials from Fennoscandia, and in these deposits there are a number of mineral species—such as olivine and apatite—which are relatively non-resistant to weathering.

Another important source is the Rhenish massif, composed of Devonian, Carboniferous, and Triassic rocks. Since the Devonian—by far the most important—contains little but tourmaline, zircon, and rutile, these three minerals are typical of the assemblage derived from this source. Of much less importance are garnet, hornblende, and staurolite. In the Jurassic and Cretaceous of northwestern Germany three sub-assemblages from the Rhenish massif can be differentiated: the Osnabrück, with proportions of tourmaline: zircon: rutile equal to 4:4:1, the Egge, with 3:6:1, and the Ems, with 4:4:1.

Another source—the Hercynian-Bohemian massif—is the area of sedimentary and crystalline rocks extending from the Harz Mountains to the Bohemian massif. Since this province is made of a number of different rock-types, the suites it has contributed are likewise varied. The Triassic of the Harz is the main source of tourmaline, zircon, and rutile in the Jurassic and Cretaceous of northwestern Germany; along with these are rare garnet, staurolite, and kyanite. In Saxony, especially in the Tertiary of Leipsig, the assemblage from the Sudeten area predominates; the principal minerals of this group are the characteristic species topaz, as well as staurolite, kyanite, and andalusite. In the upper Tertiary of lower Bavaria, the Bavarian Forest furnished zoned zircon, sillimanite, andalusite, monazite, dumortierite, and corundum. Though these three assemblages are rather different in composition, they were all contributed from one or more areas within the Hercynian-Bohemian massif.

The Alps are the chief source of heavy minerals for south Germany and for the course of the Rhine; the typical minerals of this assemblage are garnet, hornblende, glaucophane, and epidote. Present in lesser quantity are blue tourmaline,

TABLE 35. *Mineral composition of north German deposits, showing average values for the minerals of the Fennoscandian assemblage* (after Sindowski 1948)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Garnet	26	23	61	12	19	13	10	3	30	16	8	8	12	16	13	17	5	28	28	26	12
Epidote	67	—	—	4	—	—	5	1	10	1	11	16	17	2	14	10	23	5	7	10	26
Hornblende	2	—	5	—	41	—	4	2	9	1	4	47	30	2	19	22	50	20	21	60	21
Augite	—	1	6	68	34	—	—	8	11	—	—	—	—	—	—	—	—	13	5	—	1

1. Devonian, Norway
2. Devonian, Sleswick-Holstein
3. Bunter sandstone, Heligoland
4. Middle Jurassic, Pommerania
5. Wealden, Pommerania
6. Lower Cretaceous, Pommerania and Mecklenburgh
7. Eocene, Oldenburgh
8. Lower Oligocene, East Prussia
9. Septaria clay, Mayence
10. Middle Oligocene, lower Rhine
11. Middle Oligocene, Oldenburgh
12. Stettin sands, Pommerania
13. Middle Oligocene, Leipsig
14. Middle Miocene, lower Rhine
15. Middle Miocene, Hanover
16. Middle Miocene, Oldenburgh
17. Middle Miocene, Sleswick-Holstein
18. Boulder-clay, East Prussia
19. Boulder-clay, East Mecklenburgh
20. Younger boulder clay, Mecklenburgh
21. Boulder-clay, Oldenburgh

spinel, chlorite, and among the light minerals, microcline and plagioclase with inclusions. In Bavaria, the influence of the Alps is apparent from the upper Cretaceous to the modern sediments. In the oldest Pleistocene, when the Rhine flowed in the upper Rhenish basin, the Alpine assemblage predominates along the course of that river.

In Holland, around the mouth of the Rhine, the Fennoscandian and Alpine assemblages are commingled. Both assemblages have the same characteristic minerals—garnet, hornblende, and epidote—and in such a mixture it is difficult to distinguish the two. One way of telling them apart is that the Alpine assemblage contains blue and violet glaucophane and blue tourmaline; the Fennoscandian assemblage lacks these varieties, but contains greenish arfedsonite and purple tourmaline.

14. PROBLEMS AND CONCLUSIONS

The writer has given several examples of German studies of the heavy mineral assemblages found in various geologic horizons. In many cases, it has been possible to interpret the sources of the various assemblages; two main sources—Fennoscandia and the Alps—have been demonstrated for a number of different geologic horizons.

Heavy-mineral studies play an important role in solving stratigraphic and paleogeographic problems. For this reason, it is most important that the data afforded by them be interpreted correctly. Several lines of investigation need further work before they can be considered satisfactory. First is the problem of heavy-mineral resistance to weathering. Another is resistance to transportation, and the meaning of grain shape. Still another is the use of varietal characteristics of minerals in differentiating assemblages. A few remarks on each of these may serve to make the needs clearer.

With respect to weathering, and to transportation, garnet is one of the most interesting minerals. On the one hand, it is chemically unstable, so that it is etched and often completely destroyed during weathering in humid climates, during the formation of kaolin, or after deposition in sediments. But on the other hand, it is resistant to mechanical processes during transportation, and it is therefore concentrated in far-travelled sediments. For example, garnet is found in the outermost zone of influence of the Fennoscandian source, while the other principal minerals—hornblende and epidote—were destroyed before this limit was reached.

The case of zircon may be chosen to illustrate the problem of rounding. The shape of this mineral has been taken by some authors to be a clue to the mode and distance of transportation. Zircon, as crystals, is derived chiefly from granite, quartz prophyry, and other igneous rocks; in sediments and crystalline schists the grains are usually rounded. Rounded zircons are undoubtedly indicative of transportation, but Kleinsorge (1937) has shown that zircon from granite was rounded little or not at all in 60 kilometers of transportation in the Enz River (northern Black Forest). Therefore it seems that a long distance is necessary to round zircon; this travel might involve the incorporation in sediment and reworking of the grains during several different sedimentary cycles. In general, then, rounded zircons cannot be used in solving paleogeographical problems, but crystals of zircon are a good indication of a nearby igneous-rock source.

The use of varietal characteristics of minerals in differentiating assemblages is a question that has not been thoroughly investigated. Should one, for example, report "amphiboles," or should this category be divided into common hornblende, basaltic hornblence, glaucophane, and arfedsonite? The writer believes that such fine discriminations are necessary for detailed investigations of the source of heavy-mineral assemblages. Steinert (1948) has used this method in his study of the boulder-clay of Sleswick-Holstein. But it must be pointed out that in routine work, involving a large number of

separations, such detailed studies are very time-consuming.

Perhaps the most general problem is that of heavy-mineral resistance to both mechanical and chemical processes. We need especially to consider differential weathering under humid, arid, and tropical conditions, and during the formation of laterite and kaolin. The cooperation of all sedimentary petrologists is needed in solving these major problems.

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FIGS. 1–4, APRIL 1949

DO STYLOLITES DEVELOP BEFORE OR AFTER THE HARDENING OF THE ENCLOSING ROCK?

B. M. SHAUB
Smith College, Northampton, Mass.

ABSTRACT

The first step in the determination of the origin of stylolites is to establish the time when they were developed, i.e. do they antedate the consolidation of the enclosing rock or were they developed subsequently as demanded by the solution-pressure theory. The writer had previously presented photographic illustrations of stylolitic structures in the Indiana limestones and the Lockport, N. Y., dolomite that could not have been formed in hardened rock. These are further discussed and additional illustrations of stylolite structures from the Tennessee "marble" are presented as examples of stylolite seams which could only have developed in unconsolidated plastic calcareous sediments.

In 1943 Stockdale (p. 3) presented what he called a "succinct summary of the fundamental elements in the problem of stylolite origin in light of further studies and new discoveries, and because of Shaub's disregard for the preponderance of commonplace field evidence in support of the solution theory such as had already been discussed in lengthy, detailed publications (Stockdale, 1922, 1926, 1936)."

While the evidence produced in support of the solution-pressure theory has, no doubt, reached unusual proportions, that, in itself, does not prove that the solution-pressure theory is the correct answer to the problem of stylolite genesis. There have been many theories in the field of geology supported by a preponderance of evidence, yet the great amount of evidence proved to be erroneous when the facts were finally discovered. Any amount of commonplace evidence offered in support of any theory might be invalidated by a single bit of critical, diagnostic evidence which has been overlooked or not correctly evaluated.

Stockdale (1939, 1943, 1945), Bastin (1940) and Goldman (1940) apparently have not recognized the value of the evidence presented by Shaub (1939) which supports an origin for stylolites prior to the consolidation of the interpenetrating strata involved in a stylolite seam.

As a number of questions have been raised concerning the evidences presented by the writer in 1939, it appears desirable first, to discuss some of these and then present some new evidences that also show clearly that the development of the stylolite seams antedate the consolidation of the sediments.

Stockdale (1943, p. 11) claims that I ignored his extensive evidence that the clay partings "should be nothing more than a concentration of the less soluble substances of the dissolved rock." On the basis of normal sedimentary processes an examination of the possible and probable differences between the clay which has been deposited as an impurity in the limestone or in an adjoining clay seam does not indicate that one should expect any distinguishable differences between them as they both have undergone the same processes after having been derived from the same source or sources. Hence, I do not see how a comparison of the chemical analyses of the clay in the limestone and that in an adjoining stylolite seam could yield any significant diagnostic evidence bearing on the origin of the stylolites, but instead it only adds to the abundance of the so-called "commonplace evidence" which so often obscures

rather than clarifies the issue. Stockdale (1922, p. 83) stated that "The thickness of the clay caps varies in direct proportion to the length of the stylolites." In my paper (1939, Fig. 2) on the origin of stylolites I showed an illustration of two stylolite columns along a seam, one of which was 3/16 inch long and had a clay cap slightly greater than 1/16 inch thick while the other column was 1 3/8 inch long and contained a clay cap 1/16 inch thick. According to the statement just quoted the cap on the longer column should have been more than $\frac{1}{4}$ inch thick. Hence the thickness of the caps does *not* vary in direct proportion to the length of the stylolite columns. Instead, the caps are of approximately the same thickness over considerable distances along the seams and as the strength of the stylolite seam decreases the thickness of the clay caps decreases as described in detail by Shaub (1939, p. 54).

Stockdale (1943, p. 5) stated that Shaub (1939) "overlooked or undervalued the evidence pointing to the fact of rock removal." The evidences presented by the former for rock removal have been examined in detail. A trip was made to the quarries in the oölitic limestone to the north and south of Bloomington, Indiana, to examine the stylolite seams for evidences of rock removal such as Stockdale (1922, Figs. 23, 24, 25 & 27) has shown in his semi-diagrammatic sketches. Such clearcut examples of rock removal could not be found although a diligent search was made. Only examples of very doubtful similarity were observed, and none of these contained supporting evidence that rock had been removed. Hence it appears to the writer that the conception of rock removal has not been proven.

However, there is positive evidence that rock material has been displaced by plastic flow (Shaub 1939, Figs. 4 & 9) and the accompanying figures 1, 2, 3 & 4. In emphasizing the removal of rock material by solution, Stockdale (1943, Fig. 1, p. 9) has based much of his argument on the apparent cross-cutting relationship of the stylolite columns and the *color bands* in the limestone which he calls "laminations." In so doing he *assumes* that the color-band laminations are earlier than the stylolites. Could they not be later and also might there not be some unsolved phenomena relating to the origin of the color-banding or laminations? Hopkins (1896, p. 309) in discussing the cause of the color variation in the Bedford oölitic limestone states that:

> The blue is evidently the original color of at least the greater part of the stone, and is thought to be caused by iron in the protoxide form and organic matter, the buff being largely, if not entirely, derived from the blue by oxidation of the iron to the peroxide and of the organic matter to some volatile form, or some stable form, in which it unites with mineral matter in colorless stable form. The *oxidation is a continuous process, not yet complete*, carried on mainly by oxygen in solution in the meteoric water . . . . (The italics are mine, B.M.S.)

Stockdale (1943, p. 8) asks the question: "Where stylolites occur in laminated limestone are the laminae clearly cut out and removed at places where stylolites fit into the laminated bed or are they unshaped and bent around the ends of the columns as demanded by the pressure theory?" It should be noted that the *contraction*-pressure theory does *not* demand that the laminae, if they existed in the sediments prior to the development of the stylolites, should always be bent around the ends of the stylolite columns. Shaub (1939, p. 53) states that the relative transfer of material is accomplished so that "little evidence of dragging is developed except at the contacts. This is believed to be due, in part, to the contracting action which assists in pulling the material laterally by the cohesive action between the particles as the pore water is removed." In this manner the "laminations," if of an earlier origin than the stylolites, might at first glance appear to be cut out but in reality they are only displaced latterly by the contraction of the plastic sediments, some-

what like the contraction of rubber bands. This also applies to the earlier small stylolite seams. Such small seams could also be later than the larger stylolites.

Stockdale (1943, p. 8) states: "Recently, however, still more striking observations have been made to give unequivocal proof of the absence of any mashing, bending or misshaping of sediments above and beneath, stylolite columns (see Fig. 1)." An examination of his figure 1 does show clearly, to the contrary of the above statement, that the "laminations" at places have been bent and displaced. Again the color banding could be a later phenomenon and structures connected with them should not be considered as good evidence for any theory of stylolite origin, at least not until the time of the origin of the bands in definitely proven.

In my paper on "The Origin of Stylolites" (1939, p. 59 Fig. 1) I showed a stylolite column the end of which contained bent lamine, not color banding, which conformed to the outline of the column. The photograph shows distinctly that the laminae were thinned along the arc of greatest bending or of least radius, and further that the material is displaced and not removed. This piece of critical and factual evidence shows that the laminae were bent as the column, or the two sides of the stylolite seam, moved into their present positions by plastic flow, the more plastic material moving into the places of reduced horizontal pressure. This process was completely enacted before the hardening of the rock. It is a clear-cut photographic illustration of the displacement of material and not one of removal of rock material by the process of solution. Stockdale (1943, p. 8) sidesteps this bit of diagnostic field evidence against the origin of stylolites in consolidated rock by asking a question and making a statement: "Is the structure really a stylolite? Certainly it is not any ordinary single, sharply-defined stylolite column but instead appears to be a bent seam which in itself may carry miniature stylolites." The facts are that the structure photographed *is* a column and it is one of many along the seam. By the word seam I accept Webster's definition that a seam is a "line of junction," or "a thin stratum." This line of junction or thin stratum is the clay parting between the two interpenetrating layers of rock. The interpenetrating parts may have the appearance of definite serrations or they may in some cases have definite columnar proportions, the columns being nearly circular in cross-section and having a length either greater or less than the diameter of the column. *Short* columns pass gradiationally into more-or-less disk-shaped structures. The term *stylolite seam* would embrace both the seam and the interpenetrating parts of the adjacent beds whether the interpenetrating parts are columnar, sharply serrated or approach undulations along the seam to the point where the designation as a "stylolite seam" is open to question. In the sense used, the seam always passes between the interpenetrating parts of the adjacent strata and around the parts of the adjoining stylolites regardless of their outlines. The part of the clay seam along the sides of long columns is drawn down to an extremely thin layer or film while at the end of the column the seam is of normal thickness. The part of the seam at the end and around a cylindrical stylolite is developed like the deep drawing of a brass disk into a cartridge case. The column to which Stockdale's question is directed is a short one, having an apparent "diameter" of about three or four times its length, nevertheless it is a stylolite column for stylolite columns have not been defined with respect to any minimum or maximum ratio of apparent diameter to apparent length or to any other dimension. The seam in this case, as in all cases of stylolite occurrence bends around the column and there is no reason why miniature stylolites, serrated ones, or columnar-shaped ones cannot occur along the part of the seam around the end of the larger columns. If Stock-

dale wants to rule out or question a stylolite column because it has small stylolites at its end, then he must rule out the stylolites in his 1922 paper, p. 52, Fig. 21; and p. 57 Fig. 24. As real diagnostic criteria for the origin of stylolites are rather rare there is no reason for rejecting or questioning any such factual and clear-cut evidence to retain support for some other theory. The photographic evidence shows that the stylolite column in question could only have formed in soft unconsolidated sediments and not in hardened rock.

In side-stepping a problem one often inadvertently steps into another without fully realizing its significance. In the previous quotation Stockdale states that the stylolite column "appears to be a bent seam, . . . , " hence I wish to raise the question for an explanation as to how such a *small mass* of a *solid brittle* rock could be so highly deformed while solid without the adjoining rock of the same brittle material being fractured and deformed? I believe it is impossible for sufficiently high differential forces to develop in a hard brittle rock within such a limited column to cause a deformation of the order illustrated.

Reference is again made to the transverse ridges found on the stylolite columns from Lockport, N. Y. These were called "adhesion ridges" (Shaub, 1939, p. 59, Fig. 6) in allusion to the manner in which similar ridges can be made in soft plastic materials. The length of the ridges is oriented at right angles to the striations or flutings on the columns and consequently could not have originated in hardened rock according to the solution-pressure theory. The adhesion ridges on the stylolite columns as well as others produced in clay were illustrated together for comparison. Stockdale's discussion (1943, p. 7) of these is as follows: "The first assumption is that the markings in the two situations are identical, the second that they could be made only in plastic material. The fundamental question is: are true stylolites, the entire structural feature, developed in plastic sediments? Is there convincing proof that the surface markings referred to require soft sediment for their making? Shaub, himself, expresses some doubt by his statement 'adhesion ridges are *probably* not reproducible in solidified material' (Shaub, 1939, p. 58)," (Italics are Stockdale's).

This brief discussion of Stockdale's overlooks the importance and bearing of the adhesion ridges in establishing the time when stylolites developed. Parallel movement of a stylolite column relative to the column wall is required at all times by the solution-pressure theory, would prohibit the development of the adhesion ridges. The ridges show clearly that the stylolites developed before the ridges formed and that movement ceased after they were developed. As adhesion ridges can only be raised in plastic materials it is prima facie evidence that the stylolites must have originated when the rock was plastic.

An examination of my statement that "adhesion ridges are probably not reproducible in a solidified material" is desirable at this time. "Solidified material" as used would of course refer only to solidified rock materials, however, in engineering laboratories where materials are tested for their physical properties of tensile and compressive strengths it is found that hard brittle substances when broken in tension separate with an even to uneven fracture, with the fractured surface usually normal to the axis of the applied forces. The more ductile substances, as mild steels, when placed under a load which produces a stress in excess of the elastic limit, first "neck" down considerably by plastic flow and then break with a well-developed "cup and cone" fracture. The central area of the cup and the corresponding part of the cone pull apart leaving a surface of a more-or-less hackly or splintery character. This surface may be rather remotely analogous to adhesion ridges but the configuration of the surface is wholly unlike the adhesion ridges observed on the Lockport, N. Y. dolomite, and those readily made

in clay or a multitude of other soft plastic substances.

Precision measurement in the field of industrial production is controlled and executed by means of precision gage blocks having a dimensional tolerance of around 0.000003 inch. This accuracy is obtained by being able to lap extremely flat and parallel surfaces on very hard alloy steel blocks, the surfaces of which are not highly polished and have a contact area of .49 square inch as made by one manufacturer. If two of these blocks are "wrung" together a direct force of over 200 pounds is required to pull them apart. This shows that the adhesive force between the steel blocks is over 400 pounds per square inch. When the blocks are separated there has not been any deformation of the flatness of the surfaces. If, however, one were able to lap an equally flat surface on some very ductile or plastic metal as lead or gold and then were able, in the same manner, to wring two blocks together and pull the pieces apart without distorting them one might find that the surfaces on the ductile materials were no longer flat but that they were distorted due to the adhesion between the atoms of the adjoining pieces. To what extent the uneveness, if any, would approach the appearance or configuration of the adhesion ridges on the columns of the Lockport dolomite remains to be demonstrated. As the plasticity of any solid substances like the soft metals approaches that of clay and other very plastic substances which can be deformed under very light pressures the greater is the likelihood that adhesion ridges can be produced. In the other direction involving the harder and more brittle substances the probability that one could produce adhesion ridges becomes more and more remote; and when flat pieces of such hard and especially brittle substances as limestones and analogous rocks are brought together properly and then pulled apart the probability of raising adhesion ridges becomes, I believe, essentially infinitely remote or in other words impossible.

Stockdale (1943, p. 12) writes: "If the formation of stylolites hinges upon the *unconsolidated* condition of sediments in which there is 'transfer of material by plastic flow under very low differential pressure' and if stylolites in clastic rocks originate 'in the same manner and for the same reasons' as in lime oozes, then why do not sandstones and quartzites abound in stylolites?—And, furthermore, where are the stylolites that should be in shales? Then, finally, why are there no stylolites in present-day unconsolidated sediments?" As these questions pertain to my "contraction-pressure theory for the origin of stylolites" (Shaub 1939, p. 53) the answers should be clear to a number of them to those who have studied the theory with some care and are familiar with the conditions in the rock types enumerated above. The contraction-pressure theory, briefly stated, requires a condition where two plastic materials are separated by a seam or film of clay reasonably impervious to water. The material on the one side becomes gradually drier by its being dewatered causing low horizontal tension stresses while the material on the opposite side of the seam remains in a more highly plastic condition because of the inability of the water to readily escape across the film or seam. When the unbalanced stresses caused by shrinking or contracting of the drier material become large enough, a transfer of material by plastic flow occurs into the zones of tension within the drier material. The soft clay seam will be carried along with the interpenetrating parts of the adjoining beds like soft metals when they are drawn into a deep thin-walled heavy-bottomed cup.

It appears that all stylolite seams yet described occur in marine sediments and as the great bulk of the clastic sediments now exposed at the surface of the earth are terrestrial and as they do not contain the essential requirements outlined above they could not and do not contain stylolites. The "stylolites that should" *not* "be in shales" are represented by cone-in-cone structures (Shaub 1937, p. 331–

344). As to the absence of "stylolites in present-day unconsolidated sediments," the answer is partly given above. The remaining part of the answer is that stylolites could be expected if one were to visit the unconsolidated present-day marine sediments which are still in the process of formation. If these were brought to the surface and sections cut through them, I have no doubts whatsoever but that stylolites would be conspicuous in those parts, where the conditions necessary for their origin as outlined in the contraction-pressure theory, are present. Locate such strata exposed at the surface of the earth and one would have a fertile field in which to search for stylolites in unconsolidated sediments.

The first fundamental objective regarding the origin of stylolites is to fix the *time* when the structures were developed. To this end the writer has already photographically illustrated and described (Shaub 1939) a number of examples of stylolite occurrences and/or habits, none of which could have developed in consolidated rock. These examples are illustrated in figures 4 and 5 page 56, and figures 6, 7 and 9 page 59.

ADDITIONAL DIAGNOSTIC STRUCTURES IN STYLOLITE SEAMS

During the Spring of 1940 the writer first noted a structure in the so-called Tennessee marble, which appears now to be less rare than at first expected. The stylolitic marble of Tennessee has been but slightly metamorphosed. It is a dense compact limestone with very tight stylolite seams and *takes a good polish*, hence the designation of marble. This is possibly the rock that Stockdale (1943, p. 6) refers to as well as other similar materials when he wrote "Is one to believe that the superabundant and sharply defined stylolite seams of marble beds were spared the ravages of nature and survived the destructive process of metamorphism which transformed the original properties of the rock?" It must be conceded that during diagenesis the original properties of the rock were transformed and that the transformation continues as metamorphism continues, however the so-called Tennessee marble is not in reality a metamorphic marble as compared with the marbles of western New England. The change produced by metamorphism in the Tennessee rock after consolidation has not been severe, it has not obliterated or even severely modified the original sedimentary structures. During the summer of 1939 the writer visited this area and found much less evidence of metamorphism of the marbles and associated rocks than he expected. It is from the Tennessee marbles which are so abundantly displayed in the public buildings throughout the nation and which contain numerous areas containing critical diagnostic evidence along stylolite seams that the following illustrations were obtained.

The sections shown in Fig. 1 were photographed in the Spring of 1940 and are in the floor of the Massachusetts Institute of Technology at the Massachusetts Avenue entrance. The stylolite seam in the upper part of the figure shows clearly that a part of a serrated seam has been displaced from the main part of the seam or from B to A. The fault or slip planes along which the movement occurred are clearly shown. These planes together with the displaced section form a *keystone* offset of the seam. A limited and restricted offset of this order could not occur in hardened rock unless the rock around it were badly broken. If a displacement of this kind were contrasted with the beautiful flowage and displacement patterns in some of the Vermont marbles, the differences would be clear and unmistakable, the former a displacement in plastic material, the latter a displacement in consolidated rock by dynamic forces at a higher temperature. The length of section A is 36% longer than the gap in the seam from which it originated, thus showing that a considerable plastic displacement had occurred before the rock hardened. The lower part of the same figure shows another stylolite seam on the same floor where the dis-

placement of the keystone wedges E–F and D–E are complimentary. Again as in the upper illustration the length of the displaced section is greater than the space from which it was displaced. Either earlier than the consolidation of the lime muds but earlier than the formation of the displaced keystones, both operations occurring before the hardening of the rock.

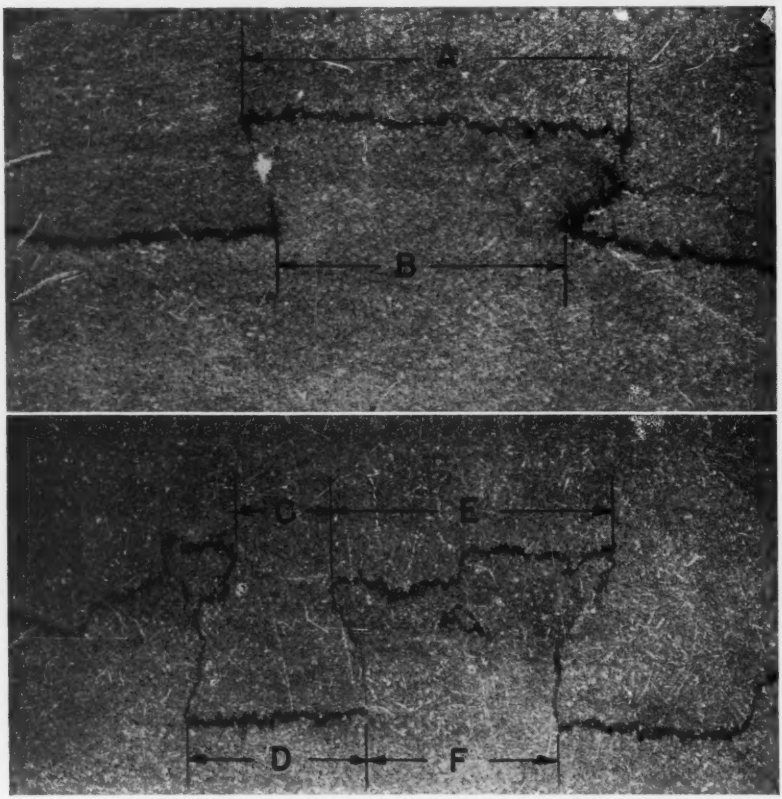

FIG. 1.—(*Top*) Wedge-shaped or keystone displacement along a stylolite seam in the Tennessee marble, photographed in the floor in the Massachusetts Institute of Technology, Cambridge, Massachusetts, Massachusetts Avenue entrance. Section A, 36% greater than B, has been removed from the latter position by plastic deformation. (*Bottom*) A section from a stylolite seam from the same floor showing complimentary keystone off-sets and other disturbances introduced along the seam by plastic flow in the unconsolidated lime muds.

the displaced sections were stretched or the gap shortened by plastic adjustment. Hence, these keystone sections or wedges present critical diagnostic evidence showing that the stylolite seams are not only

The illustration shown in Fig. 2 represents another type of stylolite seam displacement in the Tennessee marble, although it is somewhat similar to those shown in Fig. 1. In this instance the

seam is bent back onto itself, forming a kind of loop or roll. The serrations of the seam are continuous along the seam as it makes the loops at A and B. This structure shows that the *entire stylolite seam* has very locally undergone a crumpling or folding during a period prior to the hardening of the rock; the formation of the stylolites is of course the product of a still earlier development.

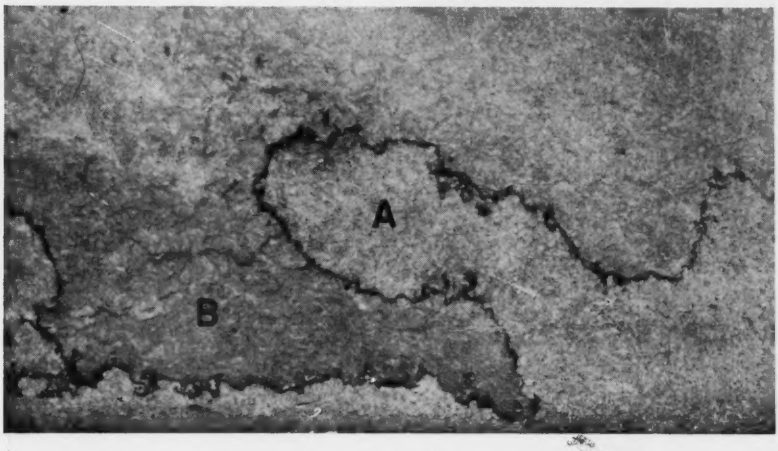

FIG. 2.—A portion of a folded stylolite seam in the Tennessee marble photographed in the steps between the first and second floors of the Carr Building in Springfield, Massachusetts. This section of the seam has been folded back onto itself during plastic adjustment, prior to the hardening of the rock, producing a completely interlocking structure. How could solution and the accompanying necessary movement produce such an irregular interlocking "saw-toothed" structure in hardened rock?

Another very instructive example of displacement of stylolite seams in the Tennessee marble is shown in Fig. 3. In this illustration a faulty plane cuts nearly perpendicularly across the stylolite seams. The illustration includes a length of about 24 inches along the slip plane. An examination of the seam along this displacement shows a number of interesting relationships. Starting at the top of the illustration one observes that there is only a slight displacement of the short stylolite seam at A. The next lower seam shows a displacement that is at least 5 times greater, while again the displacement of the stylolite seam at C is practically nil. Near the bottom of the illustration a short seam has been displaced only slightly at D while the one nearby has a very large displacement at E. An extremely interesting and important feature is that the large deflection of the seam at E is accompanied by the keystone displacement F–G nearby along the same seam. I do not believe that such pronounced differential displacements of the size illustrated could possibly occur in such limited space in a hard, relatively incompressible, brittle rock, without the adjoining material showing abundant evidence of dynamic disturbances. There are no such disturbances present. Hence, we are brought to the conclusion that the faulting and development of the differential displacements as shown and the keystone offset were produced in unconsolidated plastic sediments, and since the stylolite seams

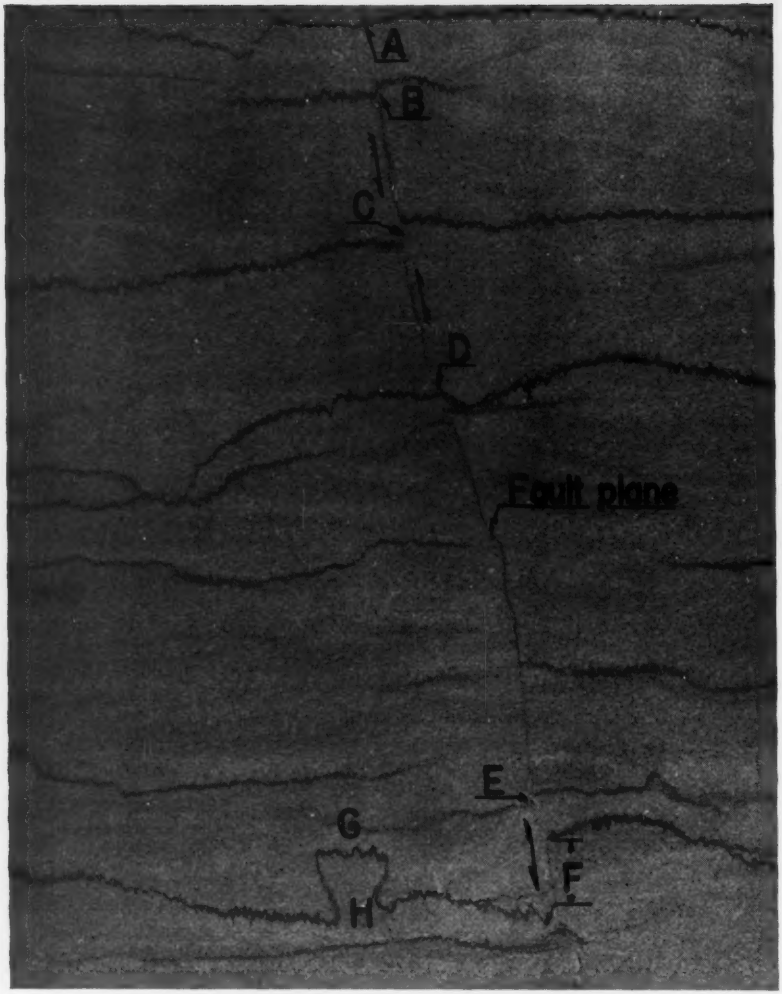

FIG. 3.—Photograph of an area about 20×24 inches in a marble panelled wall of a room in the Hotel Cleveland, Cleveland, Ohio. Note the differential displacements at B, C, D, E, and F along the slip-plane; also the keystone displacement at G–H. How could displacements of the order of magnitude shown be obtained in other than a highly plastic material? The stylolites originated at a still earlier date.

are earlier than the displacements they too were developed at a time when the sediments were plastic.

These wedge-shaped or keystone displacements and differential degrees of faulting in a relatively short distance certainly place the development of stylolites prior to the hardening of the rock and I venture the statement that they are, in themselves, far more diagnostic in placing the time of stylolite development prior to the consolidation of the rock than all of the "preponderance of field evidence" assembled by the workers in support of the solution-pressure theory. When a pertinent single critical diagnostic criterion not involving unknown or doubtful phenomena is beyond the range of a theory it is indeed time to consider the discard of the theory and to reorganize the pertinent criteria free from unknown factors and build a harmonizing theory that will account for not only the "commonplace" evidences and facts but also the rare ones, as well, and avoid being tempted to build categories of "*genuine stylolites*" and "pseudo stylolites" (Stockdale 1943, p. 1) to suit one's theory. One may follow a car track through the sands of a desert for hundreds of miles and never see the style of tread on the tire, the sands having rolled back into the track leaving a V-shaped depression. This is the commonplace track of the desert and one unfamiliar with the facts might argue that it was made by drawing a small double plow through the sand. However, at one place where the car crossed a moist depression containing plastic material the tread was impressed clearly into the clay—a rare find. Is one to throw away the rare find because it clearly shows that the track in the sand was made by some rolling object, with a peripheral surface carrying a distinct design? I think not, for the commonplace track lacked the critical diagnostic evidence; hence we must often look for the rare and unusual, instead of the commonplace, and use all rare occurrences as most important keys to the solution of problems and develop theories to account for the rare as well as the commonplace.

FIG. 4.—Figure 437, p. 633, *Geology of Canada 1863*, by Sir William E. Logan *et al.* is described as a "specimen from the Corniferous formation (Devonian) near Port Dover (Canada) in which the crystallites (stylolites) penetrate a mass of chert imbedded in limestone." Words in parentheses added for clarity. I raise the question—can the chert be more soluble than the limestone?

There is hardly a public building of any size, where the Tennessee marble has not been used and that does not contain one or more examples similar to those illustrated above. Hence, there is evidence of a like nature available to all who have a few minutes to linger and examine the many stylolite seams on excellent display. Numerous displays have been set up for many years but the advocates of the solution-pressure theory apparently either ignored, overlooked or did not appreciate the value of such structures along the stylolite seams as diagnostic criteria for establishing the *time*, at least, when the stylolites originated.

An interesting occurrence of stylolites is illustrated and described by Logan (1863, p. 633, Fig. 437). His illustration

is reproduced in Fig. 4 because of its importance in showing the manner in which the limestone stylolites penetrate a mass of chert in the Corniferous formation near Port Dover, Canada.

To account for this structure the solution-pressure theory *requires* that the chert, into which the limestone columns have penetrated, was more soluble than the calcite columns which project into the chert nodule. There are large areas of limestone terranes where chert nodules are found at the surface and which have weathered out of the limestone where they were formed. Most of these chert nodules at the surface are free from the least vestige of adhering or surrounding limestone which has dissolved and been carried away. The chert nodules retain their peculiar shapes and are essentially unaltered during the complete removal of the limestone by solution. Now, how, by all fair and unbiased deductions based on known facts, can one claim that the limestone columns in the chert were more resistant to solution than the chert? Is it not a good time, even though late, to carefully reconsider some of the so-called "solution phenomena" in rocks?

The re-examination of the chert-calcite stylolite occurrences on the basis of the known properties of these substances during both their unconsolidated and consolidated phases would, in the writer's belief, be helpful in solving some of the associated problems, the answers to which must await the correct interpretation as to the time when the accompanying stylolites were developed.

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A NOTE ON WESTERN AUSTRALIAN DIATOMACEOUS EARTHS

DOROTHY CARROLL
Linnean Society of New South Wales, Sydney, Australia

ABSTRACT

A very brief description of deposits of diatomaceous earths occurring in the southwestern part of Western Australia is given. The earths are fresh-water swamp deposits and contain *Pinnularia*, *Eunotia*, *Navicula*, and *Amphora*.

The following notes concerning diatomaceous earth deposits in Western Australia were prompted by a misquotation in the paper by H.W. van der Marel (this Journal, 17, No. 3, p. 129).

On the narrow coastal plain of the southern part of Western Australia there are numerous fresh-water swamps or lakes. Many of these are filled to varying depths with a black peaty material consisting of organic matter, diatom fustules, and spicules of fresh-water sponges. This material when calcined yields a pure white to buff-colored diatomite. The largest and purest diatomaceous earth deposit occurs in Lake Gnangara (not "Onangara" as quoted) in the Wanneroo district about ten miles north of Perth. The area of the deposit is approximately 15 acres, and is estimated to contain a million cubic yards of diatomite which in its raw state has the consistency of stiff gray mud. The amount of organic matter is sufficient for the diatomite to be self-calcining if set alight after drying. The diatoms present include *Pinnularia*, *Eunotia*, *Navicula*, and *Amphora*.

An analysis of air-dry material (Simpson, 1903) shows the earth to have the following composition:—

	%
SiO_2	49.08
Al_2O_3	3.51
FeO	Trace
CaO	0.16
MgO	0.05
Moisture at 100°C.	11.20
Moisture at ignition	35.79
	99.79
Bulk S.G.	.383

The calcined earth contains over 90% SiO_2 and weighs approximately 16 lbs. per cubic foot.

In the long dry summers the peaty material in these swamps, which may dry up completely, may be set alight and burn for a considerable time. The largest fire of this kind was at a place known as Spectacles Swamp, south of Perth. The material was calcined to a depth of three feet over several acres. It is a pinkish buff, powdery, impure diatomite, considerable quantities of which were used during the war in an attempt to control weevils in stored bulk wheat.

Diatomaceous earth of a different character occurs in the vicinity of springs and soaks in some areas. In some places it contains little organic matter and is cut into large blocks which, after air-drying, have been used for building construction.

The diatomites are of Recent age, but small occurrences of a Miocene spongolite are known from the south coast of Western Austrialia.

Many of the deposits of diatomite in the eastern parts of Australia are associated with, and often inter-bedded with Tertiary basalts. The diatoms present in,

clude *Synedra* and *Melosira*, thus differing markedly from the Western Australian diatomites in both diatomaceous content and age. Owing to the absence of organic matter they do not require to be calcined prior to use.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 19, NO. 1, PP. 39–42
FIGS. 1–7, APRIL, 1949

A NOTE ON VOIDAL CONCRETIONS IN THE EL MILAGRO FORMATION OF WESTERN VENEZUELA

L. W. LEROY
Colorado School of Mines, Golden, Colorado

ABSTRACT

Voidal limonite concretions occur abundantly in local surface weathered phases of the El Milagro formation (Pleistocene) of western Venezuela. Their development is attributed to periodic and inward progressive peripheral oxidation of claystone fragments irregularly distributed within predominantly arenaceous deposits. Volume reduction of claystone fragments by increased density of a limonite casement is believed responsible for development of the central void.

INTRODUCTION

The morphology of certain concretions is obvious, whereas developmental processes of other varieties are complicated and uncertain.

Voidal limonite concretions (Pl. 1, Fig. 5) are common in weathered outcrops of the El Milagro formation (Pleistocene) of the Maracaibo Basin of western Venezuela. These structures are unique in their development, and an epigenetic origin is established.

The El Milagro deposits appear to have accumulated under a fluviatile environment and consist essentially of coarse-grained, poorly graded, unconsolidated, tan to tannish-brown, quartzose, micaceous sandstone. Conglomeratic lentils are frequent and sporadically distributed throughout. Thin interbeds of greenish-gray to tan arenaceous claystone are discernible only in the subsurface and in fresh outcrops. Cross-lamination and lenticularity are conspicuous sedimentational features of the formation. Silicified wood fragments occur throughout. Silicified tree sections three feet in diameter and exceeding 12 feet in length have been observed. A systematic survey of the deposits should reveal an interesting vertebrate fauna.

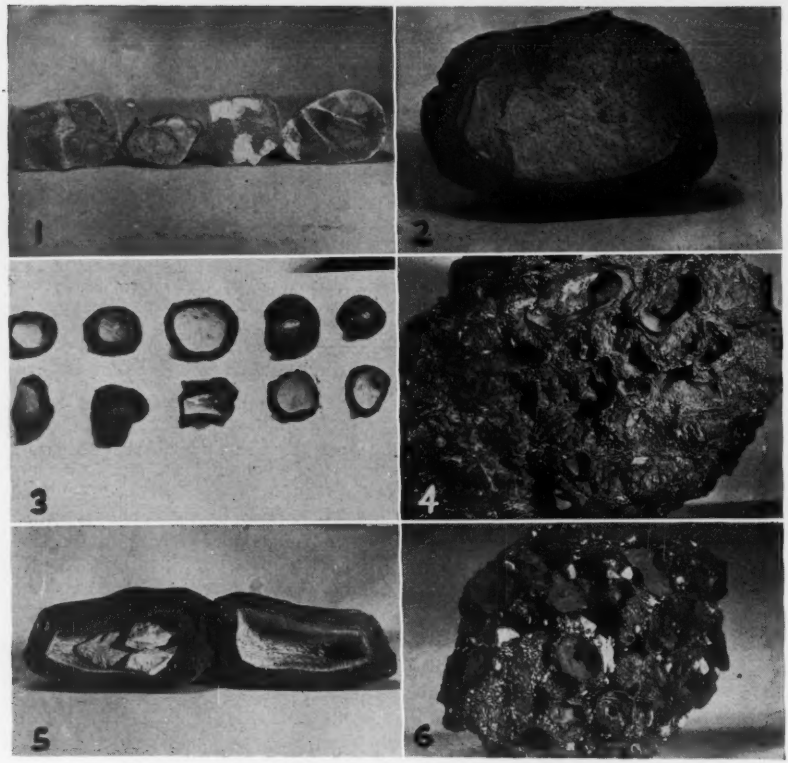
Because of its continental character, surface denudation and unconformable relationship with subjacent Pliocene, Miocene, Oligocene and Eocene deposits, the El Milagro varies in thickness from zero to at least 1,200 feet.

Light mineral fractionates consist dominantly of subangular quartz grains commonly veneered with an iron oxide film. Feldspars are present in minor quantity. The heavy detritals include ilmenite, leucoxene, zircon, tourmaline, rutile, titanite and staurolite in appreciable numbers; garnet, epidote and mica are present in moderate amounts. This suite exhibits marked affinity to those of the underlying Miocene and Oligocene sediments but differs from those of the Pliocene (Onia formation) which contain abundant muscovite, epidote, frequent hornblende and appreciable light gray schist detritus.

Excellent outcrops of the El Milagro are frequent in the El Milagro District of the city of Maracaibo. Numerous exposures may be observed along the lakeshore road one mile south of the Perijá-San Francisco highway junction and also just north of the Richmond Exploration Company camp at kilometer 2 on the Perijá highway. Specimens and material forming the basis of this discussion were obtained from the latter two localities and are deposited in the museum at the Colorado School of Mines, Golden, Colorado.

CONCRETIONARY STRUCTURES

The El Milagro concretions, all of which are totally or partially voidal in



EXPLANATION PLATE 1

FIG. 1.—Light gray, silty, unaltered claystone pebbles. Peripheral casement not yet evident in these specimens.

FIG. 2.—Claystone pebble exhibiting a rather well-defined peripheral casement; central void not yet developed.

FIG. 3.—Typical voidal limonite concretions; shows concentric banding and smooth interior surface; characteristic of final stage of concretionary development.

FIG. 4.—A cemented aggregate of voidal concretions embedded in an arenaceous host.

FIG. 5.—A typical voidal concretion with claystone residual.

FIG. 6.—A highly weathered concretionary aggregate.

their final stage of development, occur profusely and are firmly cemented in surface weathered arenaceous phases of the formation. Examination of well sections and fresh excavations has demonstrated their absence in the subsurface.

The concretions vary from irregular, ellipsoidal, subspherical to semi-cylindrical in outline. The shape of the structure is more or less controlled by (1) outline of the original claystone pebble from which it develops, and (2) stage of development. They range from $\frac{1}{4}$ to 14 inches in maximum dimension.

The first stage of concretion development involves partial peripheral oxida-

tion of tan to gray-white claystone pebbles; no banding or lamination tendencies are exhibited (Pl. 1, Fig. 1). In the final developmental stage (Pl. 1, Figs. 3, 5), the concretion consists of a well-laminated peripheral shell and a central void containing minor amounts of residual claystone. All intervening stages of development have been observed.

FIG. 7.—Showing redistributed claystone pebbles embedded in a coarse sandstone host. Some of these fragments exhibit slight peripheral oxidation, though for the most part they are unaltered.

Wall thicknesses range up to ½ inch depending on the stage of development and size of the structure. The wall is distinctly laminated, with laminae varying from paper thin to ⅛ inch. The laminae range from ocherous-yellow to brownish-red to black and exhibit sharp to gradational boundaries. As many as 12 laminae have been noted in some of the larger specimens. The shell sometimes exhibits filled and open shrinkage cracks variously oriented to laminae surfaces. These cracks frequently contain black, fibrous secondarily deposited limonite. The inner surface of the void is generally smooth (Pl. 1, Fig. 3) and undulating. Some specimens reflect narrow ridges and submammillary irregularities. The outer surface is smooth and is invariably coated by a thin layer of ferruginous sandstone.

The concretions obviously result from repeated hydration and dehydration of hard, silty, gray-white to tannish claystone pebbles derived from reworked continental Miocene, Oligocene and El Milagro deposits. A summary of their development follows:

1. Partial oxidation of a claystone pebble. In the earliest stage, oxidation is most prevalent peripherally and to some extent generally involves the sandstone host. Peripheral reddish colors gradually grade inward to greenish hues. No definite color or density bands are evident at this stage (Pl. 1, Fig. 1).

2. As oxidational processes continue, differential banding becomes more pro-

nounced. The outermost portion of the pebble increases in hardness and density. A central void is frequently initiated during this stage.

3. Stage 2 is followed by further oxidation; better definition of concentric laminae and enlargement of the central void become more evident as the density of the outer shell increases.

4. The terminating stage of development (Pl. 1, Fig. 5) involves almost complete oxidation of the claystone pebble, development of a dense outer limonitic casement and extreme volume reduction of the original pebble material. The latter accounts for development of the central void.

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APRIL, 1949

REPORT ON AN INFORMAL MEETING OF SEDIMENTARY PETROLOGISTS, XVIIIth INTERNATIONAL GEOLOGICAL CONGRESS LONDON, ENGLAND, SEPTEMBER 1, 1948

The December, 1948, issue of the *Journal of Sedimentary Petrology* reported a meeting of sedimentary petrologists in London, on September 1, 1948, in connection with the meetings of the International Geological Congress. As matters of considerable interest to students of sediments were discussed at this meeting Doctor R. Dana Russell, president of the Society of Economic Paleontologists and Mineralogists, requested Doctors Percival Allen of the University of Cambridge, England, and D. J. Doeglas of the Landbouwhogeschool, Holland, to assemble the discussions. These gentlemen have kindly done this and the discussions are published so as to be available to all students interested in sediments.—THE EDITOR.

As no section of the Congress program had been devoted to sedimentary petrology, the British sedimentary petrologists, headed by Dr. P. Allen of the University of Cambridge, arranged a meeting directly after the closing of the Congress.

Dr. P. Allen said in his opening speech that the meeting had two purposes:

1. The meeting of colleagues, with the initiation of new petrological friendships and the consolidation of old.

2. To enable British sedimentary petrologists to hear something of the flourishing schools of thought in other countries, particularly those of the Continent. Dr. A. Vatan (France) and Dr. D. J. Doeglas (Netherlands) had consented to outline the development of a newly formed organization in Europe. In Britain there was no "school," but this meeting would enable the British and others to share the enthusiasm of their European colleagues and cooperate in building up a new organization. This led to the two important questions that Dr. Allen raised for discussion:

a. Is some sort of *international union* in sedimentary petrology desirable (i.e. for the exchange of information, contacts, materials, etc.)?

b. Should some kind of *international meeting* of sedimentary petrologists be held regularly in the future?

Dr. D. J. Doeglas discussed sedimentary petrological work in western Europe. Actually an organization of sedimentary petrologists does not exist in western Europe. The contacts between sedimentary petrologists in Belgium, France, and the Netherlands is based on enthusiasm and belief in the methods of the school of Edelman. This enthusiasm and belief in sedimentary work is an important factor in achieving useful results. Too many investigators still doubt the methods used and the results obtained. It is true that the distribution of mineral associations and grain sizes frequently seem to be chaotic. This, however, is not due to the methods of investigation, but is a consequence of the interaction between erosion, transportation and sedimentation. Each sediment is a mixture. The mixture, however, does not represent all minerals of the source area. It contains only the minerals in a certain range of size. This range is not necessarily the original one. Due to the weathering of source rock and the effects of transportation, the original sizes may have decreased. Many factors, therefore, influence the mineral composition of a sediment and for fossil sediments it is practically impossible to reconstruct all of these factors.

Specialization in science is a common feature and we find this also in sedimen-

tary petrology. We can distinguish:

1. The laboratory man, who is most interested in improving methods.

2. The pure mineralogist, or mineral hunter, who studies variations in mineral species and, on a broader scale, the regional distribution of a certain mineral from a source rock into the surrounding sediments.

3. The pure "mechanical analyst," making mechanical analyses and publishing the data in graphic form or as statistical values for comparison.

4. The "heavy mineral" geologist, studying the geographic distribution of mineral associations and the relation between various sedimentary provinces and their sources.

5. The "diagenesist."

Having personally gone through all of these phases, the speaker is coming back to the oldest one in sedimentary petrology, that of the old-fashioned lithologist who studies all the megascopic features of sedimentary formations to obtain data on correlation and environment. To the megascopical features, however, microscopic data must be added. The greatest failure in sedimentary petrology in recent years has been the relative lack of field work and the exaggerated importance given to laboratory work.

For the future of sedimentary petrology, laboratory work, although very valuable to the advancement of the science, should only be used as a means of checking field observations where necessary. To understand the processes of erosion, transportation and deposition, the regional study of Recent sediments should have preference.

Dr. A. Vatan presented the regrets of Prof. Bourcart (Paris) Prof. Dangeard (Caen) and Dr. Nils Horner (Sweden) who were unable to attend the meeting. He went on to point out the need for a community of effort to cope with the rapid evolution of petrological methods, especially in the study of detrital rocks. Regional sedimentary work calls for a certain standardization of methods which only can be obtained by an organization the aims of which would be:

A. The creation of centers of documentation.

B. Team work.

A. An international center of documentation will be difficult to realize. It will need a rather large administrative organization which is expensive. Dr. Vatan suggested the creation of national centers which:

a. Collect papers, abstracts, and data of analyses published and made in their own country.
b. Publish papers on sedimentary petrology.
c. Collect typical suites of heavy and light minerals from their respective countries for exchange purposes.
d. Collect all factual data obtained by sedimentary investigations (weight percentages of mechanical analyses, percentage of heavy and light minerals, etc).
e. Supply (when requested) samples, mineral slides, reprints, abstracts, or photocopies of analysis data. The "Institut francais du Petrole," with its microfilm service, is able to supply, at cost, such photocopies for papers in the French language.

B. *Team Work.* Various problems can only be solved by team work and international cooperation. To such problems belong those in which are implied statistical data (granulometry) and tests of new methods. Dr. Vatan cited the work of Berthois, who has developed a method for the statistical measure of heavy mineral percentages, using the cube of the width of the grains. Also, studies of the Europen Triassic, Middle Cretaceous (Greensand), and the rhythmic sedimentation in the Flysch and Molasse cannot be solved in one country.

A greater cooperation between sedimentologists of the new and old world also would be useful, as many papers are not known on the other side of the ocean.

Dr. Vatan concluded by inviting the colleagues, in the name of Prof. Bourcart,

to a meeting to be held between May 24th and June 2nd 1949, at La Rochelle (France). This meeting will be the replica of a first meeting in Gand (Belgium) in 1946. Recent marine deposition on the continental platform will be especially studied. The last part of the meeting will be devoted to a study of the Pliocene and Quaternary of the Charente and of Dordogne (e.g., the well known site of Les Eyzies).

Dr. R. Dana Russell reviewed briefly recent work in sedimentology in the United States, noting particularly that there has been a great increase in the study of Recent marine sediments (partly as a result of work done by or sponsored by the Navy and partly owing to the increased interest by oil companies in the possibility of production on the continental shelves) and second, increased work on local and regional variations in sedimentary facies, again stimulated by the interest of the oil companies in the possibility of more lithologic-type traps. He mentioned, in connection with the establishment of an organization of sedimentary petrologists, that such an organization already exists in the United States in the form of the Society of Economic Paleontologists and Mineralogists (an unfortunate title for a society that consists primarily of sedimentologists, and of micropaleontologists who are also interested in sedimentation and stratigraphic problems), and that this society welcomed additional members from other countries. The *Journal of Sedimentary Petrology*, published by the Society, welcomes papers from foreign contributors. Present plans are to increase the *Journal*, either by expanding its size or by issuing more numbers each year, providing sufficient worthwhile papers are forthcoming. The *Journal*, particularly if more numbers are issued per year, could serve a useful purpose as a clearing house of information by the publication of brief notes from members and contributors.

Dr. P. Evans (Chief Geologist, Burmah Oil Company) referred to petrological work in Assam. For each section examined, frequencies of diagnostic minerals are plotted on a range table to enable a comparison to be readily made. It has been found that, in the alternations of sandstone, clay, and shale which comprise the Upper Tertiaries of the Assam region, there is a general sequence of mineral suites which can be recognized over a wide area. The appearance and disappearance of the various minerals provide "markers" which separate the different suites in the sequence and which can be used for correlation. Some markers have been traced for several hundred miles; others are of more local value. Since the Upper Tertiary of Assam is almost unfossiliferous, correlation by heavy minerals has been of considerable value.

Dr. Doeglas pointed out that long-range correlations by means of heavy minerals should be considered with care, in the same way as those made by microfossils. Studies in the Gulf Coast area by Lowman and Cogen show that true "time planes" cross micropaleo-, heavy mineral- and lithological (Schlumberger) lines. Each method gets a different result. Only a careful study of all methods will give the true picture. Projects 5 and 6 of the Reports on Projects and a Coordinated Program of Fundamental Research in Sedimentology by S. W. Lowman (A.A.P.G. Research Committee, Houston, Texas, July 1, 1947) give an extensive program for sedimentary research and show the discrepancies in present-day concepts.

Dr. W. Groves (Britain) referred to the two fundamental methods in sedimentary petrography mentioned by Doeglas, and inquired whether it was better to trace the minerals from their primary sources to their destination in the sediments or vice versa. The speaker had had experience with both types of research and stressed the fact that both methods had, as a prerequisite, a really detailed knowledge of the mineral content of the source rocks. He therefore appealed for more studies of the primary sources of sediments. It has been twenty years since, at the invitation of Prof. A. Brammall who

had just made a most detailed study of the Dartmoor granite, the speaker undertook a prolonged study of the distribution of Dartmoor detritus in the sediments of southern England. He can testify to the fact that once all varietal characters of the species of a main primary source of minerals has been established in full detail it is possible, when those minerals are present in a sediment in sufficient quantity, to identify them. Such work can not be based upon one mineral but only upon the collective degree of coincidences afforded by as many minerals as possible, and particularly by the presence of the correct varietal characteristics. In the Dartmoor study, it was possible to build up a reasonably strong case for the presence of Dartmoor detritals at some horizons and for their absence or relative paucity at others. Such work soon yielded valuable geological results; the varying trends of distribution of the detritus with passage of time, the original distribution as distinct from subsequent redistribution, the paleogeography, age of uncovering of the primary source, etc.

The speaker subsequently went to Uganda where the generally faulted relationship of the Bukoba Sandstone to the Karagwe-Ankolean, both entirely unfossiliferous sedimentary series, posed what, at that time, was an insoluble stratigraphic problem of age relationship, for the faulted junction was occupied by a line of swamps. But, having first studied the heavy mineral assemblage of the tin-bearing granites intrusive into the Karagwe-Ankolean, he was able to identify that assemblage in the Bukoba Sandstone, and also tentatively to correlate with that sandstone the Mityana and Butologo Sandstones of Uganda and the Kisii Sandstone of Kenya. Nowadays these are all regarded as belonging to the Bukoban System.

Dr. Doeglas answered that the two methods did not exclude each other. The Dutch school, however, had proved that with a few fundamental concepts (sedimentary petrological provinces, provincial alternations and successions) and the investigation of many samples regionally as well as vertically, the filling of a sedimentary basin could be understood. Detailed studies as mentioned by Dr. Groves may have to follow the less accurate but broader scale studies. The need for the distinction of mineral varieties already has been felt by the Dutch sedimentologists. More studies of the heavy minerals of igneous and metamorphic rocks will be important too, not only for sedimentary petrology but also for the origin of the igneous and metamorphic rocks. Dr. Doeglas' main point was that regional sedimentary studies should precede the detailed studies, as the conditions of deposition never will be understood by detailed studies alone.

Dr. Wanless (U.S.A.) stated that he held similar views to Dr. Groves. (No summary of his speech has been received)

Dr. Groves emphasized a point previously made by Dr. Doeglas, namely, that heavy mineral separation work on primary rocks afforded more minerals and far more information generally than could be obtained from thin section study. The high degree of concentration obtained by heavy liquid separation of crushed rocks, followed by electro-magnetic separation, is not always appreciated. In illustration, he cited two instances. Prof. Brammall almost invariably obtained, when panning the streams on Dartmoor, at least a few grains of amphibole, yet he had had to cut several hundred thin sections of the granite before he intersected any amphibole. Similarly, a hand specimen of a Channel Island granite yielded half a specimen tube of hornblende, yet no trace of the mineral was to be found in fourteen thin sections previously cut from the specimen.

Dr. Allen said that, in some ways, he held opposite views to those expressed by Doeglas. He was convinced that, in his country at any rate, future progress lay not so much in a "back to the field" movement (which was regress), but rather in *taking precise laboratory methods out to*

the field for the first time. The increased precision should be both mineralogical and petrological. Greater accuracy in mineralogical methods was badly needed, as Dr. Groves and others had pointed out. We need to know much more, chemically and crystallographically, than simply that such a detrital was, for example, "garnet." Varietal work could and should go much further. Questions of provenance would probably yield more easily (in certain minerals) to varietal studies based on the presence of trace elements rather than on optical properties, and the increasing accessibility of the mass spectrograph and isotope-analysis made direct age-determinations of certain detritals at last feasible. The second technique bade fair to revolutionize petrological work, for ideal materials (both detrital and authigenic) often occurred in sediments and the number of possible solutions to questions of provenance might be drastically reduced by its use.

Greater accuracy in petrological methods was particularly desirable along sound statistical lines. Proper statistical planning, scrutiny, control and analysis of field and laboratory research projects could save invaluable time (and subsequent acrimony). Sedimentary variation (i.e. of composition, grain size, etc., both vertically and laterally) might thus be made to help rather than to hinder. Variation is as much a characterof a sediment as any other peculiarity. It can equally well be measured. In addition, more experimental (particularly hydraulic) work was needed, especially on the deposition and chemistry of *the actual detrital minerals studied in the field.* Dr. Allen concluded by stating that, in his opinion, field and laboratory work along lines such as these would bear more fruit than the "decrease of accuracy" approach described by Doeglas.

Dr. Doeglas answered that for a good understanding of erosion, transportation, and sedimentation, many samples have to be investigated. This is not possible if methods are too elaborate. With a "less accurate method," the speaker meant a practical method, accurate enough to reveal the variations occurring in nature but not more. He further warned against statistical methods. These too should be handled with care. They can give very valuable results but their value may be easily exaggerated. Arithmetical means, medians, and sorting coefficients are only based on a few points of the size frequency distribution and do not yet give much insight into the genesis of the deposit. First we have to know why a certain size-frequency distribution occurs, and that can only be solved by a field study combined with a laboratory investigation of many samples. The same holds for variations in heavy mineral content. Many factors influence the final deposit. Often an important factor is forgotten and an explanation is based on a minor one. In our work the forgotten factor is commonly the size and composition of the source material.

At the end of the meeting the organization of a union for sedimentary petrologists was discussed. As no preliminary preparations had been made the general opinion was that the establishment of such an organization should be postponed until the next International Geological Congress. In the meantime an International Secretariat for Sedimentary Petrology would be founded. Its duties would be the collection and supply of information, including: the names and addresses of sedimentary petrologists, the type of work being done by each, methods of investigation, results, and papers.

Dr. D. J. Doeglas, Landbouwhogeschool, Laboratorium voor Mineralogie en Geologie, Wageningen, Netherlands was unanimously elected International Secretary. Sedimentary petrologists are asked to submit the above-mentioned information to the secretary to enable him to furnish the information when requested.

P. ALLEN
D. J. DOEGLAS

LIST OF GEOLOGISTS WHO GAVE THEIR NAME AT THE MEETING OF SEDIMENTARY PETROLOGISTS HELD IN THE ROYAL SCHOOL OF MINES, LONDON, DURING THE INTERNATIONAL GEOLOGICAL CONGRESS, 1948

ALLEN, P., Sedgwick Museum, Cambridge, Britain.
BOND, G., Department of Geology, University College, Hull, Britain.
BOURCART, J. J., Laboratoire de Géographie physique, 1 rue Victor-Cousin, Paris 5, France.
BATHURST, R. G. C., Sedgwick Museum, Cambridge, Britain.
BEASLEY, A. W., 53, Upper Lancaster Road, Ascot, Brisbane, Australia.
CAPEWELL, J. G., Department of Geology, University College, Gower Street, London, W.C. 1, Britain.
COATES, J., c/o Burmah Oil Company (India Concessions) Limited, 11 Gurusady Road, Ballycunge, Calcutta.
CORRENS, C. W., Institute of Sedimentary Petrology, University, Göttingen, Germany.
CRAIG, G. Y., Westerlee, Clober Road, Milngavie, Glasgow, Britain.
DUNHAM, K. C., Geological Survey and Museum, Exhibition Road, London, S.W. 7, Britain.
DOEGLAS, D. J., Geologisch Laboratorium, Landbouwhogeschool, Wageningen, Holland.
DANGEARD, L., Faculté des Sciences, Université de Caen, Caen (Calvados), France.
EVANS, P., Burmah Oil Company Limited, Geological Department, Britannic House, Finsbury Circus, London, E.C. 2, Britain.
GROVES, A. W., Imperial Institute, London, S.W. 7, Britain.
GLANGEAUD, L., Université de Besançon (Doubs), France.
HARTLEY, H., Burmah Oil Company Limited, Britannic House, Finsbury Circus, London, E.C. 2, Britain.
HEMINGWAY, J. E., Department of Geology, The University, Leeds, Britain.
KAY, M., Department of Geology, Columbia University, New York 27, United States.
KUENEN, PH. H., Melkweg 1, Groningen, Netherlands.
MIDGLEY, H. G., Building Research Station, Garston, Hertfordshire, Britain.
MACAR, P., Université de Liège, Belgium.
NIGGLI, E., Rijksmuseum van Geologie, Garenmarkt 1 B, Leiden, Netherlands.
NORIN, E., Mineralogical Institute, Uppsala, Sweden.
PROCTER, E., 16, Delph Mount, Nelson, Lancashire, Britain.
RUSSELL, R. DANA, U. S. Navy Electronics Laboratory, San Diego 52, California, U.S.A.
TAVERNIER, R., 17 rue Paul Fréderique, Gand, Belgium.
SHACKLETON, R. M., Department of Geology, The University, Liverpool, Britain.
SCHASSMANN, H., Kasernenstrasse 68, Liestal, Switzerland.
SCHWARZACHER, W., Innsbruck, Mineralogisches Institut, Universitätstr. 4, Austria.
SHUKRI, N. M., Department of Geology, Faculty of Science, Abassia, Cairo, Egypt.
VATAN, ANDRÉ, Institut Français du Pétrole, 4 Place Bir Hacheim, Rueil-Malmaison, Frankrijk.
WILKINSON, P., Department of Geology, The University, Sheffield, Britain.
WANLESS, H. R., 234 Natural History Building, University of Illinois, Urbana, Illinois, U.S.A.
WHITAKER, J. D. McD., 21, Rathmore Road, Cambridge, Britain.

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